Calculating Water Flow in Pressurized Piping Systems in Pompeii: Methods, Data and Pipelines

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Tutkin tässä työssä mahdollisuutta laskea paineistetussa vesiputkistossa virranneen veden määrää muinaisessa Pompejissa säilyneiden arkeologisten jäännösten perusteella ja teen huomioita Pompejin vesijärjestelmän eri osien toiminnasta. Kuvailen soveltuvin osin antiikin kirjallisia alkuperäislähteitä sekä modernia tutkimushistoriaa. Teen yleiskatsauksen vesijärjestelmään Pompejissa ja esitän omia tulkintojani järjestelmän joidenkin osien toiminnasta. Näitä osia ovat päävesitorni, toissijaiset vesitornit ja lyijystä tehdyt vesiputkistot. Esitän perustelut virtauslaskujen tekemiseen sopivien testikohteiden valinnalle. Testikohteita ovat korttelit V1, IX 3 ja kaksi taloa korttelissa VII 4. Esitän yleisen kuvauksen kustakin korttelista ja yksityiskohtaisen kuvauksen taloista ja huoneista, joissa on vesiputkia. Kuvailen myös lyhyesti testikohteisiin liittyvät toissijaiset vesitornit, joita ovat vesitornit numero yksi, kaksi, kolme ja seitsemän. Kuvaan yksityiskohtaisesti mahdollisia putkilinjoja toissijaisista vesitorneista testikohteisiin ja esitän perustelut putkilinjojen valinnalle. Kuvailen lyhyesti fysikaalisia virtausopin kaavoja ja ainoastaan putkivirtauslaskelmien kannalta katsottuna. Esitän myös kaavan neljännen asteen yhtälölle, jonka kuvaaja, kun se on piirretty koordinaatistoon muistuttaa roomalaisten vesiputkien muotoa ja esitän syyt miksi tätä yhtälöä voi käyttää roomalaisten vesiputkien yhteydessä. Esitän kuvauksen putkivirtauslaskelmien kulusta ja esitän tuloksia edustavin osin. Lopuksi puhun laskelmiin liittyvistä ongelmista ja esitä suosituksia mahdollisia jatkotutkimuksia varten.

Avainsanat – Nyckelord – Keywords Pompeji, putkivirtaus, roomalaiset lyijyputket
Säilytyspaikka – Förvaringställe – Where deposited
Muita tietoja – Övriga uppgifter – Additional information

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1 Introduction

Water is a necessity of human existence and presence of water has governed human behaviour as long as our species has existed. Early humans regularly visited sources of water for drinking and hunting animals for food. After the beginning of agriculture and start of sedentary lifestyle water became even more important since farming needs regular and reliable source of water be it rivers, lakes or predictable rains. Early civilizations developed multiple ways to extract and move water to desired locations. Irrigation channels, waterways and wells were extremely important to the survival of societies. Vast majority of structures related to transportation of water from source to use were initially open, but ceramic piping systems existed in Sumerian culture (Wikander 2000, 104 footnote 3). However, these were still governed by gravity and could lead water only downwards.

Start of pressurized piping systems where water runs in closed pipes is unclear, but we know from numerous examples that Romans had them at least from the first century BC onwards. They were important to urbanized Roman world basic water supply to inhabitants of cities. Also, for example for bathing which was a significant part of urban life and could not have existed in the scale it was practiced without pressurized piping systems. Considering the importance of pressurized piping systems, they are surprisingly underrepresented in Roman studies. One of the very basic aspects for studying larger impacts of piping systems is to know how much water actually flowed inside pipes. To my knowledge no one has tried to calculate accurately flow rate of a pipe –estimates for amounts of water presented in previous research are not based on calculations of flow sizes but were rather educated guesses (e.g. Hodge 2002, 299). In this thesis I try to rectify this situation, at least to some extent. I will show that flow calculations can be done with existing data about Roman piping systems. I will present what kind of data is needed and what methods could be used. My hope is that at some point in the future we have accumulated enough information about used amounts of water to start asking new kinds of questions about the use of water in everyday Roman life and maybe answer some old questions.

I chose Pompeii as the subject of my thesis for several of reasons. The most important of them is preservation level of Pompeii. We have more survived pipes and water features in Pompeii than anywhere else in Roman world. Consequently, studying piping system in Pompeii is more feasible than in other cities and towns. In the Augustan period, a new aqueduct was built in Campania and one branch brought water to Pompeii and little bit later lead pipes started to be used in the city in large amounts. It is also worth noting that the pipes we have now for research, are not all the pipes that were present when Vesuvius erupted in AD 79. Many have probably not been recorded and many have disappeared since the excavations were started in Pompeii in 1748.

My main interest is in the distribution of water inside Pompeii and so I have chosen to leave aqueducts and the main water tower outside of the thesis. Baths and public fountains are important users of piped water, but fountains do not feature complicated piping systems. Baths feature pipes, but these have not been studied or published in sufficient detail. Consequently, I decide to concentrate on pipes in private use and will present detailed information of complete piping systems in two selected city blocks (V 1 and IX 3) and description of piping systems in two *atrium* houses in city block VII 4. These were deemed suitable for test calculations based on the amount of data on the pipes.

Roman lead pipes were not round in shape as our pipes are, they were roughly pear-shaped. Many of the calculations used today to determine flow of water in pipes are not suitable for the purposes of this thesis. Consequently, I will examine physical laws that govern flow in pressurized piping systems and which types of data are needed in calculations. I examine suitability of graphical expression of Cartesian equation for Pear-shaped quartic as a proxy for a shape of Roman lead water pipe. It is also necessary to evaluate the suitability of surviving archaeological remains in Pompeii for doing these calculations.

In the chapter two I give a short overview of a surviving literary sources from Antiquity and research history. In third chapter I give a short overview of water system in Pompeii. In the fourth chapter I present an overview of the selection process for choosing test cases and detailed descriptions of the chosen city blocks and houses along with descriptions of corresponding water towers. In the fifth chapter I present detailed study of possible pipelines from corresponding water towers to the chosen city blocks and houses and calculate lengths of these pipelines. In the sixth chapter I present relevant physical laws and equations that describe pipe flow inside a pipe. In this chapter equation for Pear-shaped quartic is also presented. In the seventh chapter I describe process for calculations and present results. In the seventh and final chapter I present conclusions of this work. I also make comments and observations about different aspects of piping system throughout this work.

2 Sources from antiquity and relevant previous research

Literary sources of water pipes from Antiquity consist mainly of works of Vitruvius and Frontinus. Vitruvius wrote his treatise on ancient architecture, *De Architectura*, in the first century BC. He discusses water supply in book VIII chapter 6 describing methods of building aqueducts and storing water in cisterns. He also states that lead is poisonous and should not be used in pipes (VIII,6,10–11). Despite this knowledge, lead was widely used as a material for pipes in Italy and western Europe. Vitruvius recommends use of three-part water pipe system where parts of systems leads water to three separate user groups: public fountains, public baths and private users (VIII,6,1–2). This description has informed many modern interpretations of Roman water systems, but these kinds of systems have never been found in Roman towns and cities. Vitruvius also describes a sizing system for Roman water pipes based on the width of the lead plate needed to make the pipe (VIII,6,4). Pipes were not Vitruvius's main area of expertise so information we can find here is minimal and mainly theoretical.

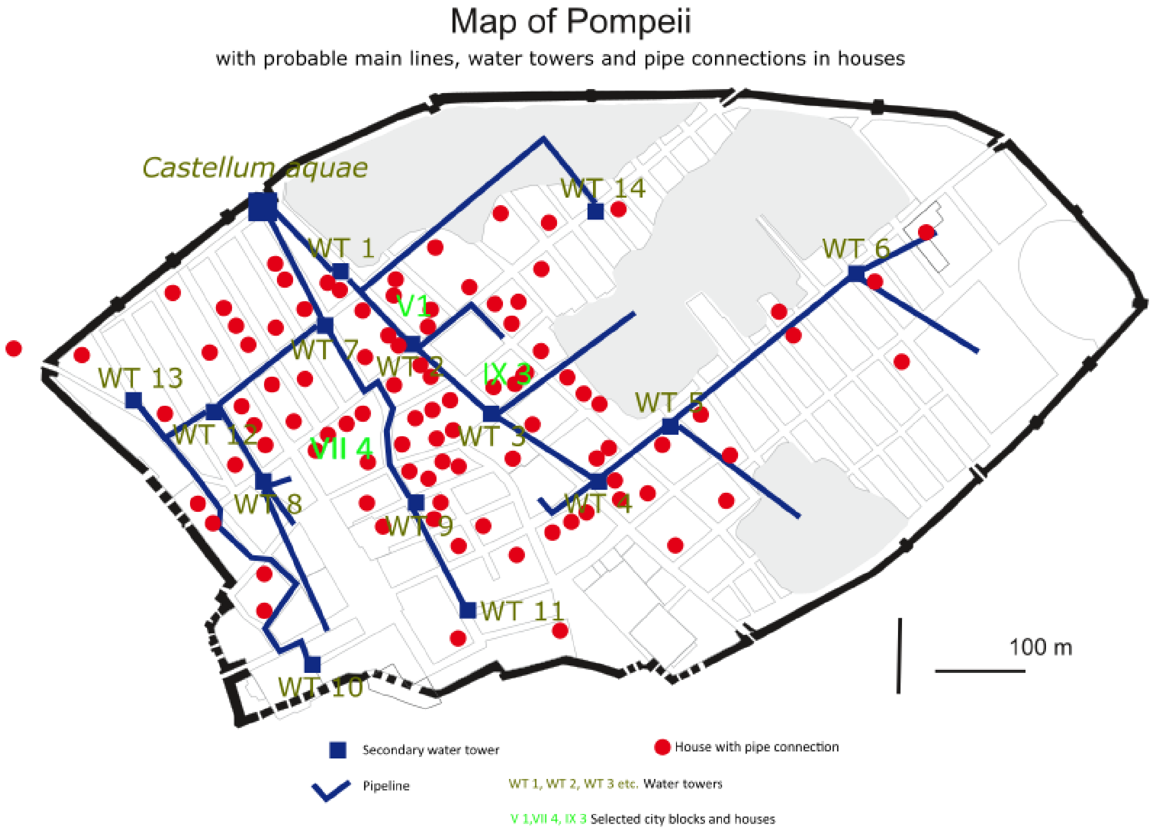
The second main source is Sextus Iulius Frontinus who wrote his book *De Aquaeductu* in the early second century AD. Frontinus was appointed as *curator aquarum* to city of Rome in AD 97so his book is more practically oriented. Most relevant information from his work is a list of Roman pipe sizes (Front. 37–63.1) which is more detailed than Vitruvius's list. These sizes have occasionally been used in research publications to describe pipes from archaeological sites. Neither of these lists are in my opinion very useful for purposes of flow calculations as we do not know how widely these recommendations were used outside of the city of Rome or if they were used even in Rome. A size of pipe was measured by weight of lead used to make pipe and it is doubtful how closely *plumbarii* followed this. This is the main reason why I do not use Roman size system for pipes in this thesis.

Several scholars have studied aspects of the water system in Pompeii and only more relevant works for this particular study are mentioned here. Trevor Hodge had studied several aspects of Roman waterworks and his book "Roman Aqueducts & Water Supply" (2002) is not only a general work but contains also many useful observations on for example manufacture of pipes. Christoph Ohlig has made an important study on Pompeii's main water tower, *Castellum aquae*. His doctoral thesis *De Aquis Pompeiorum* (2001) describes extensively this very important building. His study of how sluice gate system inside the building operated is remarkable. Jens Dykbjaer Larsen measured the eleven secondary water towers and presented data of heights, surface areas, shapes and elevations of them in an article “Water Towers of Pompeii” (1982). Thea Heres with her team studied materials and chronology of fourteen water towers and presented information of these studies in article “The structures related to water supply of Pompeii” (1993). Gemma Jansen has studied pipes many years. She and her team investigated houses in Pompeii using metal detectors and they found 63 houses with water pipes. She presented detailed descriptions of piping systems in eight houses in an article “Water Pipe Systems in the Houses of Pompeii” which was published in book “Water Use and Hydraulics in Roman City” (2001). Her doctoral thesis “Water in de Romeinse stad: Pompeji – Herculaneum – Ostia” (2002) contains important observations about pipeline connections to secondary water towers. Thomas Staub presented a very detailed and informative description about V 1, 7 Casa del Torello di Bronzo in his doctoral thesis “The Casa del Torello di Bronzo (V 1,7): Investigating a residential house and its complex water system” (2013). This includes accurate dimensions of pipes, distribution boxes and pipelines among other useful observations. Recently Richard Olsson has presented a comprehensive description of piping system in Pompeii in his licentiate thesis “The water-supply system in Roman Pompeii” (2015). He took new measurements of the water towers, calculated possible heights and other dimensions for water tanks on top of water towers and made knowledgeable observations about different parts of piping system in Pompeii.

3 Overview of the water system

Water was brought to Pompeii by an aqueduct in an open channel. Origin of aqueduct water is somewhat unclear, Serino and or nearby Avella, or both, are cited as possible sources (Ohlig 2001, 282). Whatever the source is, water entered the city through the main water tower, *castellum aquae*, which is situated in the highest point of Pompeii next to *Porta Vesuviana*, in the northern edge of the city. Here, water was first sieved to purify it from largest impurities and then it was led through a rather complex sluice gate system to three large lead pipes (Ohlig 2001, 157—239). Superficially this three-part system seems to follow the guidelines that Vitruvius laid on his book *De Architectura*. He stated that water from main water tower should be divided in three parts according to recipients of water i.e. public fountains, public baths and private users. In practise this system would have needed three parallel pipes going to all parts of the city and there is no archaeological evidence of that. In reality, these three main pipes led water to different parts of the city to be used there regardless of the recipients of the water.

Figure 1. *Map of Pompeii with some water structures and features used in this work (Modified from map by Dr Eeva-Maria Viitanen*



It must be also noted that at this point the system becomes a pressurized piping system and starts to follow physical rules that concern pipe flows. I must stress one very important aspect of pressurized piping system. Pipes need to be full of water for the system to work as intended. If a pipe was only partially full of water, there could not be pressure inside a pipe and movement of water is governed only by gravity which enables only downward movement. Either there is enough water and system works normally or there is not, and the system does not work at all. There is no middle ground here. So, system is not working if there is not enough water to fill pipes fully.

It is accepted today that there were three main lines in the city: eastern, central and western (Figure 1). The western line is still hypothetical because no main line pipes have been found belonging to this line, unlike the other two lines. However, water towers and pipe connections to houses clearly indicate that there must have been a pipeline. Olsson has argued very convincingly on behalf of this line, and I support his claim (Olsson 2015, 39). The eastern main line seemed to need the largest amount of water and in Olsson's opinion the middle pipe in the *castellum aquae*, the largest of the three, led water to the eastern main line (Olsson 2015, 29). The three outgoing pipes from the *castellum aquae* were very large: the diameter of the middle one is c. 30 cm and those of the side ones are c. 25 cm (Hodge 2002, 282). These pipes were not present when Mau excavated the tower in 1902 but openings for them can be seen and measured in front façade of *castellum aquae*. It is possible to assume that the lead pipes were salvaged after the eruption of AD 79. The water tower is on the highest point of the town and it was presumably easier to access than many other buildings that were salvaged or looted at this time.

The main lines brought water to 14 secondary water towers (Figure 1; Jansen 2002, 34; Olsson 2015, 31). Secondary water towers were rectangular in shape and varied in size and height. All the towers have one or more rectangular vertical grooves where pipes were supposed to have mainly run. A leaden water tank was situated on the top of the tower and an ingoing pipe brought water to it. The tank was at least partially open to allow water to be in

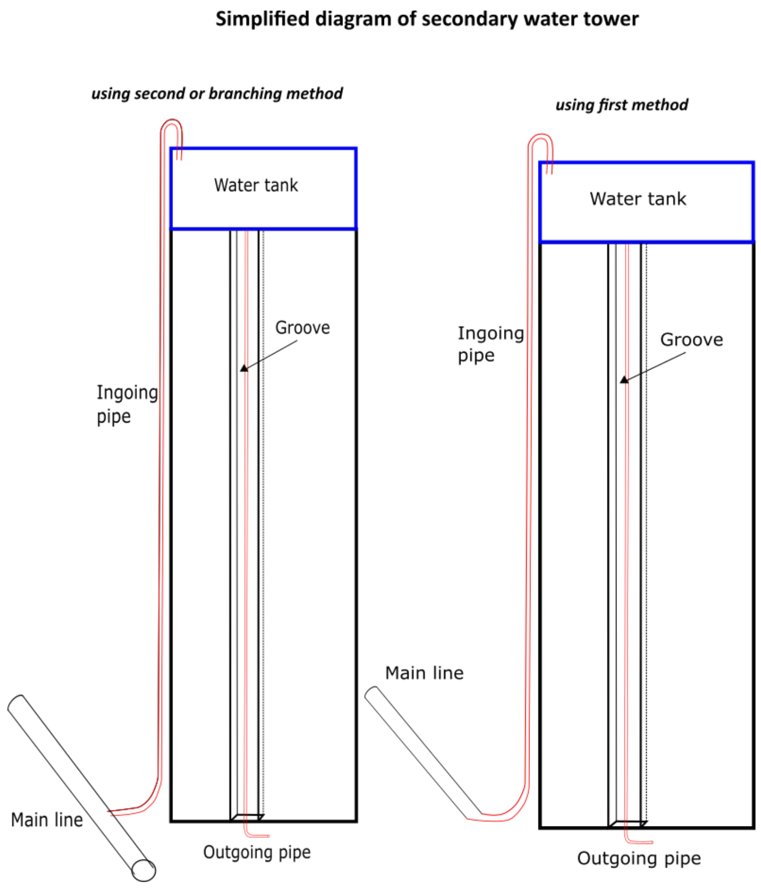


Figure 2. *Simplified diagram of possible workings of water towers. Copyright Tommi Vainikainen*

contact with the atmosphere. None of the tanks have survived to the present. (Figure 2.)

The secondary water towers had two main functions. The first and most important one was regulation of water pressure. Topography of Pompeii varies greatly and the elevation difference between highest and lowest points of town is almost 34 m (Larsen 1982). Since water pressure inside a pipe is almost entirely governed by water head, i.e. elevation difference between two points, without a pressure relief system water pressure at the lowest point of the line would be almost three atmospheres. This kind of pressure would destroy at least taps, but maybe even the pipes (Hodge 2002, 302). Water pressure was evened out in the tanks of the secondary water towers by letting water to get in touch with the atmosphere. This is the reason why tanks must have been at least partially open to atmosphere. This caused water head to reset and prevented pressure from increase to a dangerous level. Elevation level of water in a tank must be higher than the elevation level of water on the next tower in chain. Otherwise pressure could not push water inside pipe to next tank. Second main function of the water tower was to function as a distribution centre. One pipe brought water to the tank and pipes ran from top of the tower to the users nearby. It is probable that one of the outgoing pipes led water to the top of next water tower at least in some cases.

The grooves on the sides of the towers varied in size and it is generally assumed that they protected pipes from unnecessary damage (e.g. Olsson 2015, 33). In my opinion the grooves had also another, smaller function. When a pipe ran in a groove it could have been joined to the bottom of a water tank without a pipe bend. Bends are one of the weakest points in a pipeline. They cause turbulence in a water flow and turbulence erodes pipe wall from the inside. Eventually the pipe will crack, and it needs to be replaced. When the angle of bend gets smaller, turbulence increases. In modern times bends are reinforced to prevent this erosion but Roman pipes were not. I think that *plumbarii* in the Roman world were aware of this fact and tried to mitigate possible damage by not using sharp bends as much as possible. This was not always possible due to space constraints, of course, but *plumbarii* preferred more rounded bends whenever they could. This was the case with grooves where straight pipe could be used all the way to the top of the tower. However, markings in sintern incrustations on the tower walls clearly shows that pipelines ran outside of grooves too (Larsen 1982). These pipes needed a bend when they were joined to the water tank since tanks were about same size than surface area on top of the tower (see below). It is possible to make some estimations of the pipe diameters based on markings on sintern (Olsson 2015, 74).

Even though no tanks have been preserved, Olsson calculated potential heights of the water tanks based on physical properties of lead, surface area on top of a tower and weight of potential amount of water inside tanks. He is on the opinion that tanks could not be higher than little over a meter depending on the size of the tower. He also states that tanks could not have been larger than the surface area on top of a tower. Both of his observations seem very reasonable and I support them. His calculations of the heights of the towers with tanks are used in this work for tower elevations. (Olsson 2015, Appendix 1 table 1.)

How water was brought from the *castellum aquae* to the secondary water towers in practise is not clear. In Olsson's opinion the main pipelines ran to the first secondary water tower in their respective lines, where they discharged water to tanks on top of the towers. He states that these towers were water tower number 1 in the eastern line, water tower number 7 in the central line and water tower number 12 in the western line. From these towers, pipelines led water to the next tower in their respective chain of towers (Figure 1; Olsson 2015, 16). Jansen presents two possible methods of how water was distributed between the *castellum aquae* and the secondary water towers (Jansen 2002, 38). Her first suggestion is the same method as Olsson's. In her second suggestion pipelines were branched from the main lines using direct branching (Figure 2). This simply means that the branching pipe is attached to the side of the main line and a seam is soldered to be water-tight. After branching, the main line would have continued further to the next tower or possibly to the one of bathing complexes.

In my opinion both methods have problems. Using the first method would create great potential of hydraulic shock or water hammer, as it is commonly known, especially in the eastern and central lines where distances between the *castellum aquae* and the first water towers of respective lines were relatively short. Hydraulic shock is a destructive and potentially dangerous shock wave in flowing water, in other liquid or even in gas that is usually caused by a sudden stop of flow at one point (Nakayama & Boucher 1999, 244). This stoppage causes a pressure shock wave that is opposite to the direction of the water flow. When this shock wave collides with water still running to its original direction consequences could be serious often leading to ruptures in pipes or worse. Usually this stop is caused by sudden closure of tap or valve (Nakayama & Boucher 1999, 244), but another cause is when too much water tries to enter too small a pipe too fast. This creates backlash and hydraulic shock. This could be mitigated by gradually shrinking diameter of the main pipe. Problem in the second method is that pressure in the pipes further along the line could become too high which could rupture pipes. It is possible or maybe even probable that both methods were used at the same time. For example, in the eastern line the second method could have been used with the first and maybe the second tower and after that the first method could be have been used for the rest of the line. This hybrid method would sidestep both problems mentioned above: danger of water hammer and danger of pressure growing too high. If a combination of both methods was used, the pipes in the main lines should gradually shrink to prevent water hammer and direct branching should be used only with the first couple of towers of their respective lines to prevent pressure growing too high. The combination of methods could also quite easily facilitate possible main lines bringing water to large public baths. This has been a subject of some discussion among scholars researching water system in Pompeii (e.g. Olsson 2015, 61—63). Until we find new pipes connecting to a water tower *in situ*, we cannot be sure what method was used in which cases.

From the secondary water towers the water was conducted to various users in piping systems which include pipes, distribution boxes and taps. It is often said that one characterising aspect of Roman water system was constant flow of water. However, Richard Olsson (2015, 88) has made important clarifications on this in the case of Pompeii. He divides the water distribution system in Pompeii in two categories: In constant flow to public use consisting mainly public fountains throughout the city and interruptible flow in private use and in some public baths. Constant flow to public fountains means that there was always overflowing happening, but this water was not wasted as it was used to clean streets. In contrast to this, water used in private premises were often restricted by usage of taps.

Roman pipes in pressurized systems in central Italy were almost always made of lead. Lead is poisonous, but as a material it has several advantages. It is resilient, has high tensile strength, is easy to shape, has relatively low melting point and was cheap. Lead was melted and poured in a mould to get a sheet. The sheet was bent over a round bar to obtain a tube and the seam of the tube was sealed. There were three main ways of doing the sealing: The open seam could be filled with molten lead or one edge of the sheet could be turned over another and hammered until the seam was tight. The most common way, however, was to turn edges over one another to form a tight spiral (Hodge 2002, 309). The manufacturing process gave Roman pipes their typical pear-shaped form. According to Hodge, the most common length of one pipe is ten Roman feet which is a little less than three meters and is based on Vitruvius (VIII,6,4) (Hodge 2002, 309). Pipes were connected to each other when they were laid in their location of use and the joints between pipes were sealed using molten lead.

Branching was made either with distribution boxes or direct connections. Boxes were also made of lead and the typical shape is cylinder, but other shapes were also used for example in the house V 1, 7 room b which has large circular base and smaller circular top (see below). The boxes could have one or more incoming lines and one or more outgoing lines. Jansen gave figure of 22 for a total number of distribution boxes in Pompeii (Jansen 2001, 30), but new ones have been found since then for example in peristyle of V1, 7 (Staub 2013, 95) and in room 105 in IX 3, 18. Direct connections were simply pipes attached to side of another pipe so that water could enter it from main pipe.

Romans had one type of tap called a rotary tap. Mostly they functioned valve-like by controlling flow to one or more branches, but occasionally a tap was situated at the end of the line to control water flow in that point. Taps were always made of bronze. A Roman tap has an inner cylinder and an outer casing. The casing has two short bronze pipes attached to opposite sides of it and the actual pipes were joined to them. The inner cylinder has a hole running through it. Water flowed through the tap when hole was parallel to the pipes. When the cylinder was turned, the hole was no longer aligned to the pipes and water flow ceased. The cylinder was only loosely attached to the casing and if water pressure increased too much, it would have been forcibly removed from the casing which is potentially dangerous. This is the reason why taps were the weakest point of any Roman piping system. (Hodge 2002, 322–326.)

The water running in most systems in Roman Italy was calciferous. The calcium in the water congregated to the inner surface of all conduits, whether open or closed and formed incrustations called sintern. This was a major problem and aqueducts, pipes etc. had to be cleaned or replaced periodically. Otherwise conduit would be clogged, and flow would stop. (Hodge 2002, 228.)

There were three main uses for water in Pompeii. The most important one was public fountains. These were situated around town so that the distance to the nearest fountain was never much longer than one city block. There are 43 public fountains in Pompeii. (Olsson 2015, 48.) The second group was public baths. It is possible that at least some of the public baths got their water straight from the main lines. Private baths got their water from water towers. The third and last group is private users. Private use was dedicated mainly for display and showing of social and economic status of owners of large private houses. Very rarely was pressurized water used for utilitarian purposes. Some houses had pipeline for kitchen (see below city block V 1, 7) and occasionally commercial establishment had a pipeline too (see below city block IX 3, 19–20). (Jansen 2001, 37.)

I have presented different parts of water system in Pompeii. As a whole it is relatively well known, and we can reconstruct its operation rather well despite some gaps in our knowledge. In the following chapter, I will present more detailed descriptions of various parts of the system in several private contexts.

4 City blocks and water towers

The first task in the archaeological part of my study was to find suitable city blocks and houses in Pompeii. The criteria for selection are, in descending order of importance: availability of detailed data (publication or other sources), number of water pipes, location and variety of users –i.e. private, commercial or utilitarian. As a starting point, I used the map displaying the number of water connections in each city block (Figure 1)[1]. Inspection of the map gave me several promising candidates: city blocks VII 2, VII 4, VII 12, VI 14, V 1 and IX 3. Next, I inspected the availability of source material for each of these and it became clear that city blocks V 1 and IX 3 were the best choices. The city block V 1 has been studied by the Swedish Pompeii Project (SPP) and their data is being published on a web site (http://www.pompejiprojektet.se). In addition, a member of the project, Dr Thomas Staub (2013), has written his doctoral thesis on one of the houses Casa del Torrello di Bronzo (V 1, 7), with great number of pipes and other useful data. City block IX 3 has been studied by the Finnish research project *Expeditio Pompeiana Universitatis Helsingiensis* (EPUH) and the material was made readily available for this study by the project. The data available also included pipe dimensions and elevations, which are necessities for calculating pipe flow. In addition, I worked in the project during 2013 and was familiar with the material. There were also data available from houses VII 4, 31/51 and VII 4, 56 in two articles by Prof. Frank Sear (2004; 2006). These data were detailed enough for flow calculations, so these two houses were added to test cases. In the end, the availability of suitable data turned out to be deciding factor in the process of choosing test cases. Most publications do not contain information about pipe dimensions. I hope that this situation will be remedied in the future publications.

Water towers presented in this section of my work are the origins of the pipelines that lead water to the chosen city blocks and houses. Four towers were described: water tower 1, water tower 2, water tower 3 and water tower 7 (Figure 1). Water tower 1 was source of water to the northern part of city block V 1, water tower 2 was source for southern part of city block V 1 and probably for houses VII 4, 31/51 and VII 4, 56, water tower 3 was source for city block IX 3 and water tower 7 was a possible source for houses VII 4, 31/51 and VII 4, 56.

[1] The map was originally compiled by Dr. Eeva-Maria Viitanen using multiple sources that had been published by ca. 2010.

City block V 1

City block V 1 is situated in the northern part of Pompeii (Figure 1). In its western side it is flanked by Pompeii's *cardo maximus* (modern Via del Vesuvio), in the south by town's second *decumanus maximus* (Via di Nola), in the north by Vicolo delle Nozze d'Argento and in the east by Vicolo di Caecilius Iucundus (Figure 3). Via del Vesuvio and Via di Nola were the main arteries of town so the city block's location was central. The largest private houses in this block are Casa del Torello di Bronzo (V 1, 7), Casa di C. Iucundus (V 1, 23–26) and Casa degli Epigrammi Greci (V 1, 18). Relatively many commercial establishments were also present here including a bakery in the north-western part (V 1, 14–15). The city block has a fairly complex building history, but since the purpose of this study is to examine water usage in the last phase of Pompeii, it will not be discussed here (for more information see Leander Touati 2010). A map of all observed pipelines has been published by Anne Marie Leander Touati (2010, 17). Elevation data for this block was taken from web site of Pompeii Bibliography and Mapping Project[2]. The city block has numerous water pipes and other structures related to them and in this section, I have listed them together with some commentaries. The actual measurements are in Appendix 1. Data has been gathered from the SPP publications and from the project's website. In this list the houses are ordered by their entrance number.

[2] http://digitalhumanities.umass.edu/pbmp/?page_id=1258 accessed 10.9.2019.

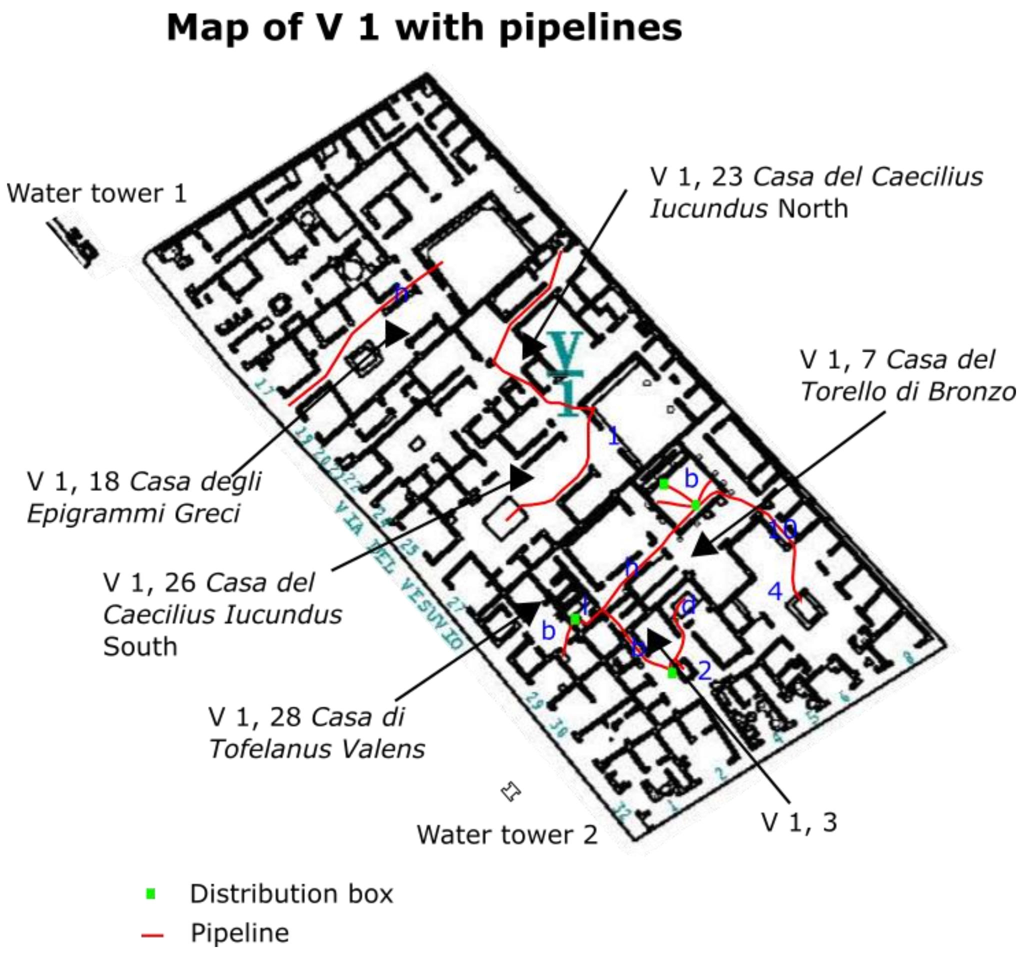


Figure 3. *Map of V 1 with pipelines and distribution boxes (modified from map in Leander Touati 2010 by author)*.

House V 1, 3

This is a small *atrium* house and it has water pipes in three rooms. All three pipes are parts of the same pipeline. The house was earlier part of Casa del Torello (V 1, 7), but was separated from it at an unknown point of time. This is also reflected in the water system of the house, which is a continuation from Casa del Torello (V 1, 7) (Figure 3). Source of piped water in this was probably water tower 2.

Room b: This is narrow corridor that originally lead to Casa del Torello but was sealed off at some point. The water pipe is buried under the floor in the western side of the corridor and ran from Casa del Torello in the north to *atrium* in the south. No measurements were available. (SPP 2019.)

Room 2: In the *atrium* of the house a water pipe ran from room b to a distribution box in the northwestern corner of the *impluvium* which is situated in the middle of the room. The *impluvium* had two fountains. The distribution box is cylindrical in shape and one incoming pipe is connected to its northern end. Another pipe emerges from its western side and continues towards west. Still from the western side a short pipe with two taps emerges. From the southern end of the cylinder a short pipe with one tap emerges. No measurements were available. (SPP 2019.)

Room d: *Nymphaeum*. From the *atrium* the water pipe ran presumably to northeast and could be seen in *nymphaeum*. The end of the water pipe is visible at the foot of the western bench. Line presumably ran from *atrium*. No measurements were available. (SPP 2019.)

House V 1, 7 Casa del Torello di Bronzo

Casa del Torello di Bronzo is an extensive *atrium* and peristyle house with numerous water pipes and other structures related to them (Figure 3). The house was named after a small bronze statuette of a bull found on the rim of *impluvium* in room 4. The house was the subject of Dr. Thomas Staub's doctoral dissertation, which is the source of information for this chapter (Staub 2013). According to Staub (2013, 93) the water pipeline entered room l (kitchen) from room b in Casa di Tofelanus Valens (V 1, 28) in the west. Point of origin of supply line was water tower number 2 in the corner of the city block VI 14 (Figure 1). Measurements of the pipes, distribution boxes and taps are catalogued in Appendix 1.

Room l: The first main distribution center with two distribution boxes is located in room l, a kitchen in the western part of the house. Five lines can be observed there. One pipeline headed towards the *atrium* in house V 1, 3. The largest of the lines probably went to the second main distribution box in room b (peristyle). One line might have headed to room h, where a pipe can be observed. The destination of one line is unknown, but Staub (2013, 94) postulates that this might have headed to a small, presumably privately-owned water fountain between entrances V 1, 3 and V 1, 4 on Via di Nola. The last one brought water to a now lost water heater in the same room.

Figure 4. *Double distribution box in V 1, 7 room l (Photo SPP/Hans Thorwid)*

Two distribution boxes were found side by side in a small niche in the lower part of the eastern wall (Figure 4). Distance between them is only 40 mm. Both are cylindrical in shape and a short pipe with tap connects them. One pipe emerges from the western and eastern ends of both boxes. The pipes from western end run northwards and from eastern end towards southeast. Both of these latter pipelines contain taps. From the northern box a pipe with tap runs towards east. A water heater was probably situated in a niche on the north side of this room, but it is now lost. This heater presumably fed water to the bath in room 20 situated next to this room. (Staub 2013, 94.)

Room h: A water pipe is visible in the central service area in the inner corner of a bench in the southeastern corner of the room (Staub 2013, 53). This presumably served the kitchen area. (Staub 2013, 94.)

Room b: Second main distribution center was in the peristyle (room b). A large distribution box here features eight pipes emerging from it. One line is for incoming water from the first main distribution center in room l. One line led to a secondary water distribution box near *nymphaeum* and served its three fountains and the basin’s seventeen small water jets. One line headed through corridor 10 to the *atrium* area in room 4. One served a pipe with tap mentioned by Mau and two served other three fountains in the peristyle. The destinations of two lines are unknown.

The large circular distribution box with smaller circular top is situated in the southern part of the garden area in the peristyle (Figure 5). From this box eight pipes emerge, four of them with taps. A second smaller distribution box is situated west of the basin in front of the *nymphaeum*. The *nymphaeum* is situated along the wall in the northern part of the garden and it features three *aedicula* fountains. The central one probably had water jet and the side *aedicula* probably featured free flowing fountains from where water flowed down some stairs to a basin situated in front of the *aedicula* (Staub 2013, 89). In front of the *nymphaeum* there is another shallow basin with a water jet. In southeast part of portico one column was removed and a wall was built between them. Small cavity is situated in this wall, where two pipes are still visible. A pipe from large distribution box feed water to this installation. In the western portico similar arrangement was built. A pipeline from the small distribution box feed water to two pipes in this installation. In addition, several discontinued pipelines can be observed around the *nymphaeum* (Staub 2013, 91). According to Staub (2013, 95), Mau observed in 1876 a pipeline with a tap at the end of line attached to the second column of eastern portico. This would indicate some kind of practical use, but this installation is now lost. (Staub 2013, 95—97.)

Figure 5. *Large distribution box in V 1, 7 room b (Photo SPP/ Hans Thorwid)*

Room 10: Pipes are visible under the northern wall and the southwestern corner of the southern wall in the corridor that runs from the peristyle to the *atrium* (room 4). (Staub 2013, 95.)

Room 4: The third and final distribution center is located in the *atrium* (room 4). The *atrium* had three fountain complexes in and around its *impluvium* and the secondary distribution box served them. The box is now lost, and the pipes have not survived, but cuttings for them are still visible on the floor. (Staub 2013, 96.)

House V 1, 18 Casa degli Epigrammi Greci

Casa degli Epigrammi Greci is a large *atrium* and peristyle house combining two or more separate entities. The eponymous Greek inscriptions were found in room y. According to map in Leander Touati 2010 a pipeline runs from entrance V 1, 18 through rooms a (*fauces*), b (*atrium*) and h (corridor) to room i (peristyle). However, the available documentation on project’s website is lacking descriptions at the moment and I have to rely on visual observations on published photographs. In the *fauces* the pipes have not survived. In the peristyle the pipes have not survived, but cuttings for them are visible on the floor. Presumably the origin of the supply line is water tower number 1 in the southeastern corner of city block VI, 16 (Figure 1).

Room h: Water pipe running from room b (*atrium)* in west to room i (peristyle) in east can be seen at the foot of the southern wall in the corridor. No measurements were available. (Leander Touati 2010; SPP 2019)

House V 1, 20–21 Taberna

Map in Leander Touati 2010 indicates that this *taberna* has water pipes. After closer examination of documentation and photographs it is obvious that the line marked as water line is actually a covered drain line.

House V 1, 23 Casa di Caecilius Iucundus – North house

Casa di Caecilius Iucundus is an extensive double *atrium* and peristyle house named after its owner Caecilius Iucundus. It consists of two houses (V1, 23 and V 1, 26) joined in the Augustan or Early Imperial period. The project's website currently lacks documentation of this house apart from some photographic documentation, but the map in Leander Touati 2010 shows a pipeline from room n (*culina*) running through rooms m (corridor) and l to a structure in the northeastern corner of room g. The available documentation maps also show either a pipeline or a drainage line that runs from the street in the east through room a (*fauces*), room b (atrium) and room i (corridor) to same structure in room g. This line is marked as drainage line in Leander Touati 2010. The origin of supply line is presumably water tower 1 since it is closer to the entrance of the house than water tower 2. The line continues from structure in room g towards house V 1, 26 through room l' (corridor). (SPP 2019; Karivieri & Forsell 2007.)

House V 1, 26 Casa di Caecilius Iucundus – South house

The southern part of Casa di Caecilius Iucundus is the larger house in this double *atrium* complex. The famous wax tablet archive naming Caecilius Iucundus as the owner of this complex, was found in room q.

Room l: A pipeline continues from room l' in house V 1, 23 to a distribution box still *in situ* in the northeastern corner of portico in the peristyle. The line forks here in two parts. One supplied water to a fountain on top of a small dividing wall between two columns. This pipeline continues from the fountain further to the east to an unknown destination. Several fragmented pipes have been found at the foot of perimeter wall on the street side. The other pipeline from the distribution box heads towards the atrium (room b) in the west. Map in Leander Touati 2010 shows that the line goes through room i (*tablinum*), but in the documentation of *tablinum* there is no sign of that. No measurements were available. (Leander Touati 2010, 123; Karivieri & Forsell 2007, 130; SPP 2019.)

House V 1, 28 Casa di Tofelanus Valens

Casa di Tofelanus Valens is a small house, which was named after its supposed owner. It is possible that somewhere in the premises production activities related to water took place (SPP 2019). As mentioned before, Staub (2013, 93) states that a water line to Casa del Torello (V 1, 7) runs through room b in this house. The pipeline is also marked on the map in Leander Touati 2010. However, there is no mention of this in the online written or photographic documentation of the house. One photograph (Staub 2013, 259) shows a pipeline entering house V 1, 7. Measurement can be found in Appendix 1. (Staub 2013, 93.)

City block VII 4

City block VII 4 is situated in the central part of Pompeii. It is irregularly shaped which traditionally has been regarded to indicate an early dating for its foundation (Sear 2004). It is limited on the north side by Via della Fortuna, on the east side by Vicolo Storto, on the south side by Via degli Augustali and on the west side by Via di Foro. The city block is fairly large and consists of several types of buildings. Most of the houses are small shops and workshops, but in the eastern part of the block there are several large luxurious *atrium* houses. Temple of Augusta Fortuna is situated in the corner of Via della Fortuna and Via di Foro. Eastern part of block was studied and documented by The Australian Pompeii team. Results of the team’s work have been published in several articles and books. Prof. Frank Sear published two articles in “Papers of British School of Rome” series (Sear 2004; Sear 2006) about the water systems of houses VII 4, 56 (Casa del Granduca) and VII 4, 31/51 (Casa dei Capitelli Colorati) and these articles contained enough information for the purpose of my thesis.

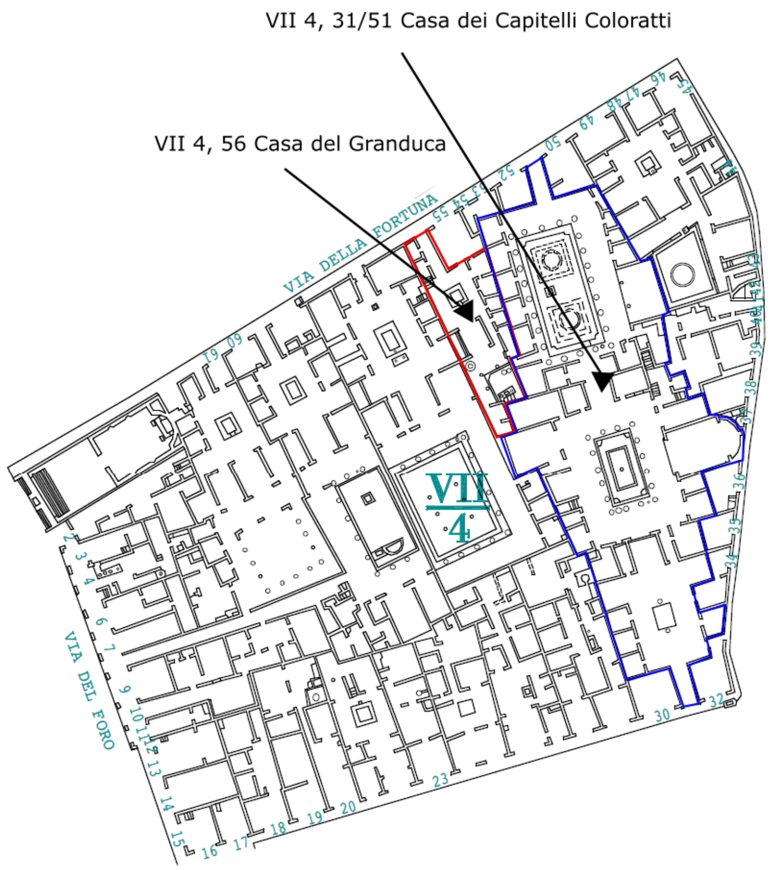


Figure 6. *Map of VII 4 with houses VII 4, 31/51 and VII 4, 56 marked. Map by Parco archeologico di Pompeiin, modified by author.*

House VII 4, 31/ 51 Casa dei Capitelli Colorati

This is a large and luxurious double *atrium* and peristyle house that runs through the whole city block and has entrances to both Via della Fortuna and Via degli Augustali. In the eastern side the house is partly limited by Vicolo Storto. Pipes and traces of pipes have been found in several rooms, but the overall picture of the system here is difficult to reconstruct. The first question here is the entrance point of pipeline to the house and that is addressed in the following chapter in detail.

Although pipes have been found only in three places several other markings, like cuts in rims of gutters, suggest that this house had rather complex piping system. Sear states that there were fountains in four different rooms, and each were fed by piped water. In addition, there was a line that fed water to the neighboring house VII 4, 55. To control water flow inside pipes Sear suggests a distribution box in room 18 (southern peristyle). In addition to this, I think it is possible that a second distribution box was situated in room 40 (northern peristyle), probably somewhere near southern columns. Sear (2006, 173–178) suggests that the garden water installations here, including a fountain, needed piped water. Also, the pipe entrance to VII 4, 55 is near and all this indicates a need for a second distribution box. No pipes were found in this room however.

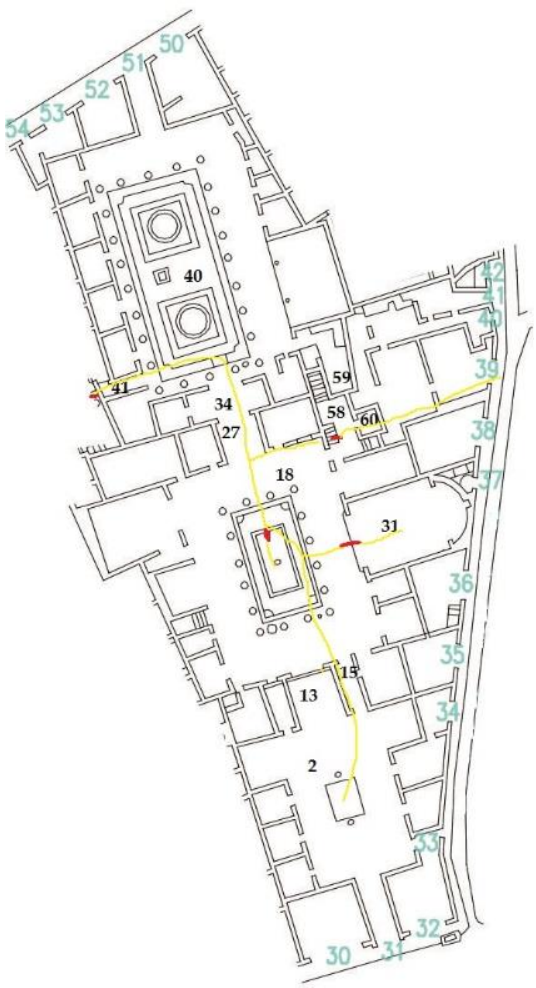


Figure 7. *Map of VII 4, 31/51 with hypothetical pipelines (yellow) and survived pipes (red). Map by Parco archeologico di Pompeii, modified by author.*

Flow calculations in this house are possible only in three locations: in room 58, at the pool in room 18 and at the threshold to room 31.

Room 58

In this room a pipe can be seen under the second step of stairs that runs to upper the floor at the west wall of the room. Measurements are presented in Appendix 1. (Sear 2006.)

Room 18

This is the southern peristyle of the house. In the middle of the peristyle there is a pool that has been interpreted as a fishpond. In the middle of this is a pedestal presumably for a fountain. In the north wall of the pool runs a pipe downwards below a plaster layer probably leading water to the above-mentioned fountain. Sear gives c.8 cm as a diameter of this pipe, which seem unnecessarily large for a fountain. Perhaps this size indicates increased need of fresh water for fish breeding and possibly further strengthens interpretation of this pool as a fishpond.

Around the pool can be observed several cuttings on the rim of gutters and stylobates surrounding the pool. Sear interpreted these as cuttings for pipes and this seems reasonable. One of these cuttings is 7 cm wide, which indicates that pipes that ran through these cuttings had a lesser diameter than the pipe in the north wall of the pool. From the middle of the eastern side of the pool parallel cutting leads toward room 31. Under the threshold between rooms 18 and 31 a pipe can be seen leading to room 31 and to a possible fountain in that room. Studying photograph of this threshold diameter of approximately 5 cm can be obtained.

Sear suggests that there once was a distribution box in this room to divide the line most likely to three branches. One went to the pool, one to north towards northern peristyle and third to south toward *impluvium* in room 2. Line to room 31 branches from this line. Measurements are presented in Appendix 1. (Sear 2006.)

House VII 4, 56 Casa del Granduca

This house is a small *atrium* house located along the northern side of block VII 4 and its entrance opens to Via della Fortuna. It is wedge shaped which Sear interpreted to indicate that plot was once owned by owners of neighboring Casa dei Capitelli Colorati (Sear 2004, 129). This claim is further strengthened by the existence of a water pipeline that entered Casa del Granduca from Casa dei Capitelli Colorati. Pipeline is clearly visible in room 13 (peristyle) of this house (Sear 2004, 151) although it is not visible from the other side of the wall in Casa dei Capitelli Colorati (Sear 2006, 175). This house has a modest piping system that fed water to *aedicula* fountain on room 13 and to now lost ornamental fountain on the edge of *impluvium* on room 2 (*atrium*). Origin of this pipeline is unclear and since it entered the house from Casa dei Capitelli Colorati this problem is addressed in that section of this study and is studied in greater detail in the following chapter. All the information in the following section is from Sear 2004.

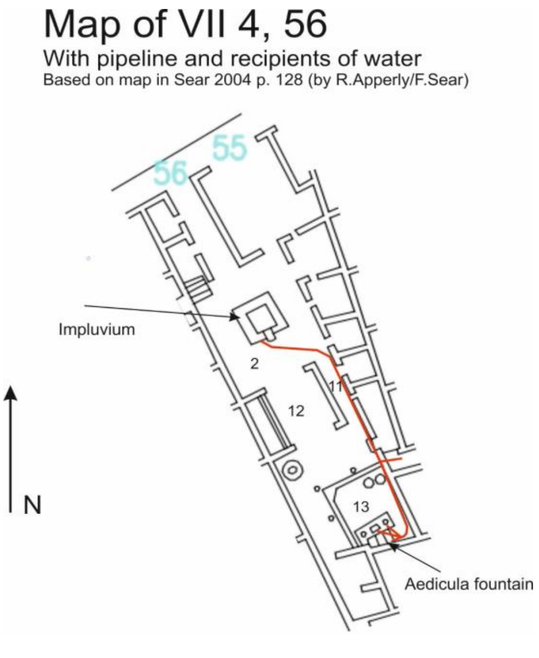


Figure 8. *Map of VII 4, 56 with pipeline. Map by Parco archeologico di Pompeii, modified by author.*

Room 13: This room is peristyle of the house. A pipeline entered house here from the neighboring house. Water pipe is clearly visible on the surface of the eastern wall at the height of 43 cm. Immediately below the entrance point is a masonry structure that Sear interprets as a possible place for distribution box. This seems reasonable since from this point the pipeline branches in two directions. One line goes to north and one goes to *aedicula* fountain which is situated in the southern wall of this garden. According to the documentation of G. Bechi in 1835 the pipeline was divided into four branches and fed water to different parts of the fountain. Two pipelines, that fed water to now lost statue and steps inside the fountain's niche, are visible today. One pipe is also visible in the top of the base that is situated on the middle of water basin immediately in front of niche. Presented measurements are in Appendix 1. (Sear 2004, 151—160.)

Room 11: Pipeline is visible at the north side of threshold between room 11 and room 2. Measurements are presented in Appendix 1. (Sear 2004, 153.)

Room 2: This is the *atrium* of this house. The pipeline continues diagonally from the threshold between rooms 2 and 11 to the *impluvium* in the middle of the room. Pipes were laid inside of older ceramic pipeline. Measurements of this pipe are in Appendix 1. (Sear 2004, 151.)

City block IX 3

This city block is located one block south of city block V 1 on the eastern side of Via Stabiana, which is a continuation of Via del Vesuvio (Figure 1). In the north there is a narrow alley between IX 3 and the Central baths (IX 4). In the east, there is a fairly quiet street, Vicolo di Tesmo. The southern street is continuation of Via degli Augustali from the west and it was a busy shopping street. The city block consists mostly of small and medium sized commercial premises but contains also one large private house, Casa di Marcus Lucretius (IX 3, 5/24) and three smaller private houses. Lead pipes were found in three houses. Data in this chapter is obtained from Finnish project's documentation, photographs and database. In addition, data concerning House IX 3, 19–20 was generously shared by Dr. Nicholas Monteix, the director of the French project studying bakeries in Pompeii. I wish to express my sincerest gratitude to Finnish project and Dr. Monteix for letting me use their data and documentations in my thesis. I also wish to express my gratitude to the people in Finnish project for all the support I have received during the years. Actual measurements are in Appendix 1.

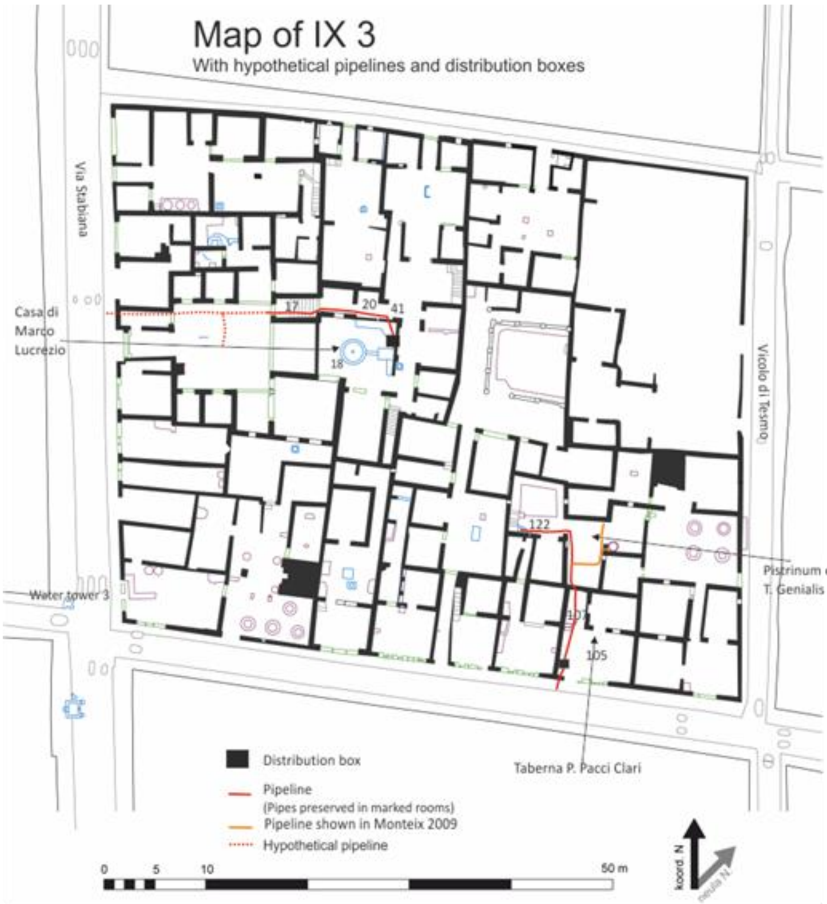


Figure 9. *Map of IX 3 with actual and hypothetical pipelines (Map by Maija Holappa/EPUH and modified by author)*

House IX 3, 5/24 Casa di Marcus Lucretius

This is a fairly large *atrium* and peristyle house named after its supposed owner Marcus Lucretius. It is famous for its garden, statue collection and wall paintings. Pipes have been found in four rooms and they form one pipeline. The point of origin for the supply is probably the water tower number 3 in the southeastern corner of city block VII 2 (Figure 1). The route of the pipeline from the tower to the house is unclear and is addressed in detail in the following chapter. After the line entered the house – either through room 1 (*fauces*) or room 3 – it went to room 2 (*atrium*) and ran along the northern wall and continued to room 17 (staircase). In room 2 there was now lost *impluvium* which could have featured a water fountain – however the line southwards drawn in Figure 9 is strictly hypothetical. From room 17 line ran in small cutting along southern wall of room 19, room 20 and room 41 to room 18 (garden), where main consumer of water, fountains, were located.

Room 17: Staircase between rooms 2 and 19. A section of a lead pipe was found during excavations coming from below the threshold between rooms 2 and 17 and continuing towards the stairs in room 17. Another section of a lead pipe can be seen in the middle of the stairs in the south side sloping down to west (Figure 10). These two pipes are part of the same line. Line continues to room 19.

Figure 10. *Pipe on the stairs of room 17 IX 3, 5/24 (Photo EPUH/ Tiina Tuukkanen).*

Figure 11. *Pipeline in rooms 20 and 41 IX 3, 5/24 turning to room 18 (Photo EPUH/ Tiina Tuukkanen).*

Rooms 19–20 and 41: From room 17, the pipeline arrives in the higher level of the house in the southwest corner of room 19. From there it runs eastwards in a narrow cutting along the southern wall of rooms 19 and 20. A long section of a lead pipe was visible in room 20. The line continues then to room 41 and almost immediately turns south and runs into a semi-circular cut at the bottom of a low pluteus wall between rooms 41 and 18. (Figure 11.)

Room 18: The garden had *aedicula* fountain and a round water basin. Water line entered room from room 41 in the north and led along the eastern wall to a distribution box. The pipe and the box are directly on top of a masonry gutter running along the east wall. Cylindrical distribution box (Figure 13) is situated north of the *aedicula* fountain in the center of the eastern wall. The supply line entered the box from the north. Exit line with a tap leaves the box to west next to the exterior wall of the basin. In the excavations of the area, a lead pipe was found placed diagonally by the basin. It was not connected to the line coming from the box and its end could not be excavated due to danger of collapse. It could be in its original position, but this remains uncertain – the top layers of the garden could have been disturbed by maintenance of the plants and the structures after the excavation in 1847. Another line leads towards south and supplied water to *aedicula* fountain – the water probably flowed out of the wineskin of the statue of Silenos placed in the *aedicula*. Two pipes could be observed in the western wall of the basin: one in the upper part and another in the bottom part. The upper pipe was most likely an overflow channel, but the function of the lower pipe is unclear. In the middle of the basin there is a round pillar with a protruding bronze pipe. This might indicate a water jet installation.

Figure 12. *Distribution box of room 18 IX 3, 5/24 (Photo EPUH/ Tiina Tuukkanen).*

House IX 3, 18 Taberna P. Pacci Clari

This is a small *taberna* in the southeast corner of the city block. A pipeline entering room 105 from the southern street was found. It continues through room 105 and enters room 107. A distribution box was also found in the southwestern corner of room 105. The water was not used in house IX 3,18, but the supply served the house next door, IX 3, 19–20. The supply line's point of origin is probably water tower number 3 in southeastern corner of VII 2.

Room 105: The line enters the room through the wall west of the entrance and enters a cylindrical distribution box soon after (Figure 13). Only one exit line was observed emerging from the box, which is unusual. The lump on top of the box could possibly be interpreted as another exit, but this remains highly uncertain. Line continues towards room 107 in the north and goes under threshold between rooms 105 and 107 before entering room 107. Measurements can be found in Appendix 1.

Figure 13. *Distribution box in room 105 in house IX 3, 18 (Photo EPUH/ Tiina Tuukkanen).*

Room 107: Pipe continues from room 105 under the floor and emerges to surface near northern wall. Then it enters narrow travertine channel and goes through northern wall to room 121. Measurements can be found in Appendix 1.

House IX 3, 19 – 20 Pistrinum di T. Genialis

This house was a large bakery. It has been studied jointly by EPUH and French project "Pistrina: les boulangeries de l'Italie romaine" which research Roman bakeries. Data is available from both the French project and from EPUH's documentation. Water pipeline entered house through room 105 and 107 in house IX 3, 18 to room 121.

Room 121: This room was excavated by the French team (Monteix 2009). The pipeline in this room is remarkably well preserved and shows some interesting features. (Figure 14.) It enters the room from room 107 in south and runs first along the southern wall and then along western wall to the threshold between room 121 and room 122. The line branches in the middle of western wall and crosses the room to eastern wall where it branches again. One branch runs diagonally up the wall and leads to basin at the southeastern corner of room 118. The other branch runs towards north to an unknown destination. After studying measurements and photographic evidence it became clear that pipes used in this room are not uniform in diameter. Particularly pipes where junctions are situated are noticeably larger than other parts of the line (Figure 15), but also in straight or bent parts of the line there is variation in the diameter of the pipes. Same kind of irregularities can be observed also in the V 1, 7 where there is also accurate enough data available. This is hardly surprising considering the manufacturing method of the pipes and the lack of uniform mass production in Roman world. Nevertheless, it is important to recognize this fact.

Figure 14. *Pipes in room 121 from the north. Notice diagonal branch on eastern wall. (Photo copyright Pistrina: les boulangeries de l'Italie romaine).*

Figure 15. *Branching of pipeline near west wall. (Photo copyright Pistrina: les boulangeries de l'Italie romaine).*

Room 122: The line along the western wall of room 121 continues north towards the threshold to room 122. After that it disappears from sight. In the southwestern corner of room 122, there is a staircase going upstairs and underneath the stairs there is a small alcove. At the bottom of the alcove, low rounded walls outline a triangular shallow pool. In its south edge, there is a rectangular base and in the wall above the base, small mouth of a lead pipe was visible at the height of c. 0.6 m (Figure 16). Presumably this is a continuation of the pipe visible at the threshold. The water could have sprouted from a statue on the base – however, no statue has been reported.

Figure 16. *Pipe visible in room 122 of house IX 3, 19–20 room 122 (Photo EPUH/ Matti Mustonen).*

Comparison between city blocks

City blocks V 1 and IX 3 are fairly close each other. Only city block IX 4, where Central baths are located, separates them. Both are centrally located along the town's main *cardo maximus*, Via del Vesuvio/Via Stabiana, which is also a main artery of pipelines indicated by the number of water towers along the street. Both contain luxurious houses and commercial premises. Perhaps biggest difference in location is that V 1 is located along another main street, Via di Nola, unlike IX 3. This would presumably give city block's shops and workshops better visibility to potential customers. Overall superficial inspection might indicate that there would not be huge differences between city blocks and they water usage. However, V 1 had considerably more water pipe structures than IX 3 and they were also more complex. Reason for this is that in city block V 1 there are four big luxury houses – V 1, 18 Casa degli Epigrammi Greci, V 1, 23 Casa di Caecilius Iucundus (north), V 1, 26 Casa di Caecilius Iucundus (south) and V I, 7 Casa del Torello di Bronzo – compared to only one big luxury house in IX 3 - IX 3, 5/24 Casa di Marcus Lucretius. On the other hand, large piping system in room 121 of IX 3, 19–20 is exceptional in commercial premises in Pompeii. This might be compared to possible pipe leading water from room I in V 1, 7 to street fountain between V 1, 3 and V 1, 4 mentioned above in section about V 1, 7.

House VII 4, 31/51 Casa dei Capitelli Colorati is also a large luxury house fully comparable to luxury houses in V 1 and IX 3. Curiously state of preservation of pipes here is not in a same level than in V 1 and IX 3. VII 4, 56 Casa del Granduca is much smaller than the other houses discussed here although it is an *atrium* house. Sear thinks that this house was owned by the same owners than VII 4, 31/51 (Sear 2004) which is probably a reason why this house had piped water.

Figure 17. *Water tower 1. ©Jackie and Bob Dunn, www.pompeiiinpictures.com*

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Water towers

In this section I describe the basic data for the four water towers relevant to my study material. Data in this section is from Larsen 1982, Heres 1994 and Olsson 2015. (Figure 1.)

Water tower number 1

This water tower is situated at the southeastern corner of VI 16 in the northwestern side of the intersection of Via del Vesuvio and Vicolo di Mercurio. It is freely standing and stands partly on pavement and partly on street. (Figure 17.) It was made of tuff, limestone and cruma blocks (Heres 1994, 46). It was probably built before AD 62 (Heres 1994, 46). The top of the tower has crumbled. Interestingly Larsen gives different height for the tower than Olsson, 6.20 m and 6.67 m respectively. There is no explanation given for this discrepancy, but Olsson’s figure is used in this study. Olsson estimates that the tank on top of the tower was 1.0 m high (Olsson 2015, Appendix 1 table). Measurements are (Larsen 1982; Olsson 2015, Appendix 1 table 1):

Base: 1.24 m X 1.2 m X 1.2 m X 1.2 m

Height: 6.67 m

asl at street: 34.7 m

asl at top w. tank: 42.6 m

Water tower number 2

This tower is situated at the southeastern corner of VI 14 in northwestern side of intersection of Via del Vesuvio, Via della Fortuna and Via di Nola. It is freely standing on a vacant space at the corner of said city block. (Figure 18.) It is made of bricks of which 60% were reused (Heres 1994, 46). According to Heres (1995, 47) this indicates that the tower was made after AD 62. Tower has crumbled off the top, but only by a small amount.

Figure 18. *Water tower 2. ©Jackie and Bob Dunn, www.pompeiiinpictures.com*

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Olsson estimates that tank was 1.0 m high (Olsson 2015, Appendix 1 table 1). Measurements are (Larsen 1982; Olsson 2015 Appendix 1 table 1):

Base: 1.5 m x 1.5 m x 1.5 m 1.48 m

Height: 6.35 m

asl at street: 32.2 m

asl at top w. tank: 39.7 m

Water tower number 3

This tower is situated at the southeastern corner of VII 2 in northwestern side of intersection of Via Stabiana and Via degli Augustali. It is freely standing and stands partly on pavement and partly on street. (Figure 19.) It was made of bricks. According to Heres (1994, 48) most of the tower was built after AD 62. Some crumbling can be observed on top. Olsson estimates that tank was 1.0 m high (Olsson 2015, Appendix 1 table1). Measurements are (Larsen 1982; Olsson 2015 Appendix 1 table 1):

Figure 19. *Water tower 3. Copyright American Academy in Rome. Photo by Esther Boise Van Deman. Taken from https://pompeiiinpictures.org*.

Base: 1.04 m x 1.2 m x 1.04 m x 1.2 m

Height: 6.05 m

asl at street: 29.0 m

asl; on top w. tank: 36.2 m

Water tower number 7

Water tower 7 is situated at the north-east corner of city block VI 13 and at the south-east corner of Vicolo dei Vettii and Vicolo di Mercurio. It stands partly on the street and partly on the side pavement. (Figure 20.) It was made of tuff and is rather poorly preserved (Heres 1994, 49). Calciferous depositions on the wall above the top of the tower indicate that the original height of this tower was considerably taller than in present time (Larsen 1982, 57) and this has to be considered when estimating original height of the tower for the calculations. Gemma Jansen (2002, 41) has studied calciferous deposits on the surface of the water tower, and she reports fifteen markings of the pipelines on the surface of this water tower. This tower was included in this list because it is a possible source of water to houses VII 4, 31/51 and WII 4, 56.

Figure 20. *Water tower 7. Photo by Stanley A. Jashemski from The Wilhelmina and Stanley A. Jashemski archive in the University of Maryland Library, Special Collections. Used under Creative Commons license. Taken from https://pompeiiinpictures.org*

Olsson estimates that tank was 1.0 m high (Olsson 2015 Appendix 1 table 1).

Estimated measurements of the tower are (Larsen 1982; Olsson 2015 Appendix 1 table 1):

Base: 1.06 m X 1.06 m X 1.06 m X 1.06 m

Height: 4.9 m

asl at street: 35.6 m

asl on top w. tank: 41.9 m

As stated above, none of the water tanks have survived to present. One tank on top of water tower 6 at the northeastern corner of the city block II 2 survived until modern times but is now lost (Olsson 2015, 33). Olsson's calculations of the heights of the towers with tanks are used in this work for tower elevations. (Olsson 2015, Appendix 1 table 1.)

5 Measuring distance between water tower and point of water usage

In order to measure distance between pipeline's point of origin – i.e. water tower –and point of water usage, careful research of the potential routes of pipeline was essential. In the case studies, very little is known of line's route outside of the houses. The pipeline is usually rather well known inside the houses and the unknown part of the line outside the city blocks V 1 and IX 3 is a relatively small part of the line's total length. In the case of city block VII 4, on the other hand, major part of the length of the whole line runs outside the houses and is unknown. Quite often the most promising route seems to be self-explanatory, but nevertheless it has to be studied carefully. In this chapter I examine potential routes for each house, choose one that I feel is most likely, and argue for choosing that particular line.

The length of the line was measured twice in two different ways in order to compare results and possibly establish if either is clearly superior. As a general rule one significant figure in decimal numbers for measurements and two significant figures in decimal numbers for means were used. First measurements were taken with an automated measurement tool developed by the Pompeii Bibliography and Mapping Project[3]. However, this map tool does not support close zooming and the course of pipeline is not as accurate as I would have wanted. In the second method the length was measured manually using RICA maps and a good ruler. RICA maps are reasonably accurate and in scale to 1:1000, but the same problem occurred as with the web-based tool, i.e. the course of the pipeline is slightly inaccurate. To mitigate this problem and potential human error five measurements using the web tool and five manual measurements were taken. Then a mean was calculated for the results of both methods and finally, a mean was calculated from these. This result was deemed to be accurate enough. However, this two-step method was used only in the first case, city block IX 3. After this experiment, the web-based tool was proven to be superior and it was used exclusively with the rest of the city blocks and houses. The final step was to add the height of the corresponding water tower to the result to get the final measured length of a pipeline

House V 1, 7 Casa del Torello di Bronzo

[3] https://www.arcgis.com/home/webmap/viewer.html?webmap=080c47adf4ff4a0eb1b274e0bb3cbb23&extent=14.4764,40.7448,14.5001,40.7565

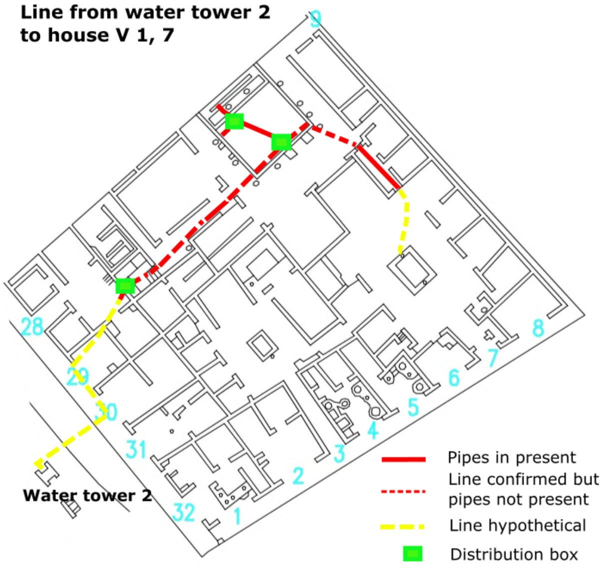

Figure 21. *Map of V 1, 7 with pipeline from water tower 2. Map by Parco archeologico di Pompeii, modified by author.*

The origin of the pipeline here is most likely the water tower 2 at the corner of the city block VI 14. It is probable that the line crossed the street immediately in front of the house V 1, 30 and then turned north. From there the pipeline probably turned east to enter the north part of the shop in house V 1, 29. Then the line went through the wall to room f of house V 1, 28 and continued through its northeastern wall to room b of the same house. Here a pipe can be seen in the partition wall between room b and room l in house V 1, 7. It is seemingly placed diagonally compared to the wall and probably came from the direction of room f of house V 1, 28. Even though a pipeline passing through two properties before entering house V 1, 7 seems more unlikely than a route passing just house V 1, 28, the diagonal pipe is sufficient evidence for the route through two houses. Staub (2013, 93) mentions that here pipeline is divided into two separate branches which then entered separately room l to connect with each part of the double distribution box in that room. This arrangement seems needlessly complicated and reason for this unclear. Possibly the amount of water needed in house V 1, 7 was so great that large distribution box was deemed necessary to assure sufficient water flow. From here on the course of the line is reasonably clear. It has been presented in chapter 3 and is not repeated here.

The piping system in this house is complex and measurements for length were taken from several parts. First from the tower to the double distribution box in room l and then from this to the second large distribution box in peristyle (room b). From there two sections were measured separately: first, the line to the smaller distribution box in front of the fountains in the peristyle and second, the line to threshold between rooms 10 and 4. There are no preserved pipes after this threshold, so it was decided to calculate the flow at this point and a hypothetical line to the fountain in room 4 was not measured. The height of the water tower 2 is 6.35 m (Larsen 1982 and Olsson 2015, Appendix 1 table 1). Larsen mentions some crumbling at the top of the tower and a small amount should be added to this, 5 cm was added to measured height. This gives a figure of 6.40 m which is used in all calculations for this tower. Results are shown in table 1.

Tower to box 1 in room l	From box 1 to box 2 in room b	From box 2 to box 3 in room b	From box 2 to threshold between rooms 10 and 4	Total to box 1 in room l	Total to box 2 in room b	Total to box 3 in room b	Total to threshold between rooms 10 and 4
27.1 m	20.58 m	5.06 m	14.38 m	27.1 m	46.68 m	52.74 m	62.06 m

Houses VII 4, 31/ 51 Casa dei Capitelli Colorati and VII 4, 56 Casa del Granduca

Before I was able to measure the length of this line I needed to study where the line entered the city block. Sear suggests that the line entered the house VII 4, 31/51 through workshop/shop VII 4, 39–41 (Sear 2006, 175). He bases this on a lead pipe found under the staircase in room 58. This pipe's diameter is c. 8 cm. Larger pipes were used – and are still used – to transport larger amounts of water from one place to another and small pipes, that branched one way or another from larger pipes, were used to bring water to the point of consumption. Pipe with a diameter of c. 8 cm is quite large for a pipe inside a house and it is likely that pipes of this size can be considered as a main line inside of houses. House V 1, 7 has pipe that has a diameter of 5.5–6.3 cm. This pipe brought water from main distribution box in kitchen area to secondary distribution box in garden area and is clearly a main line inside the house. Pipe here is even bigger and that makes it likely to be a main line pipe. Sear (2006, sivut) also thinks that VII 4, 39–41 was owned by the owners of *Casa del Capitelli Colorati*. All this suggests that the entrance point was near room 58. The most direct and most likely route goes from the entrance VII 4, 39 through rooms 69 and 68, through wall between rooms 68 and 60 to the observed pipe in room 58. This route is used in this study.

Another important question is the origin of the pipeline. If the entrance of the line to the house was through VII 4, 39, then there were two possible water towers for this: Water tower 2 and water tower 7. Shortest route is from water tower 2 (168.2 m from water tower 7 compared to 144.8 m from water tower 2, measured using the web tool). It is impossible to say from the available data which one was the line's point of origin. However, since the route from the water tower 2 is considerably shorter, it was used in this study. It is impossible to accurately present the route to entrance VII 4, 39 where the pipeline presumably entered the city block. However, the following route is one possible and that was used in this study. The line ran from the tower to corner of Via della Fortuna and Via del Vesuvio where it turned to west to follow Via della Fortuna. In the corner of Vicolo Storto the line turned to south and crossed the street. From there it followed Vicolo Storto to entrance of VII 4, 39. The whole line is presented in Figure 22 and its length to room 58 in house VII 4, 31/51 is 144.8 m. The rest of the line is described in chapter 3 and not presented here. Total lengths to room 18 and to the threshold between rooms 18 and 31 in house VII 4, 31/51 and to *aedicula* fountain and *impluvium* in VII 4, 56 are in table 2. These measurements include the height of the water tower 2, 6.40 m.

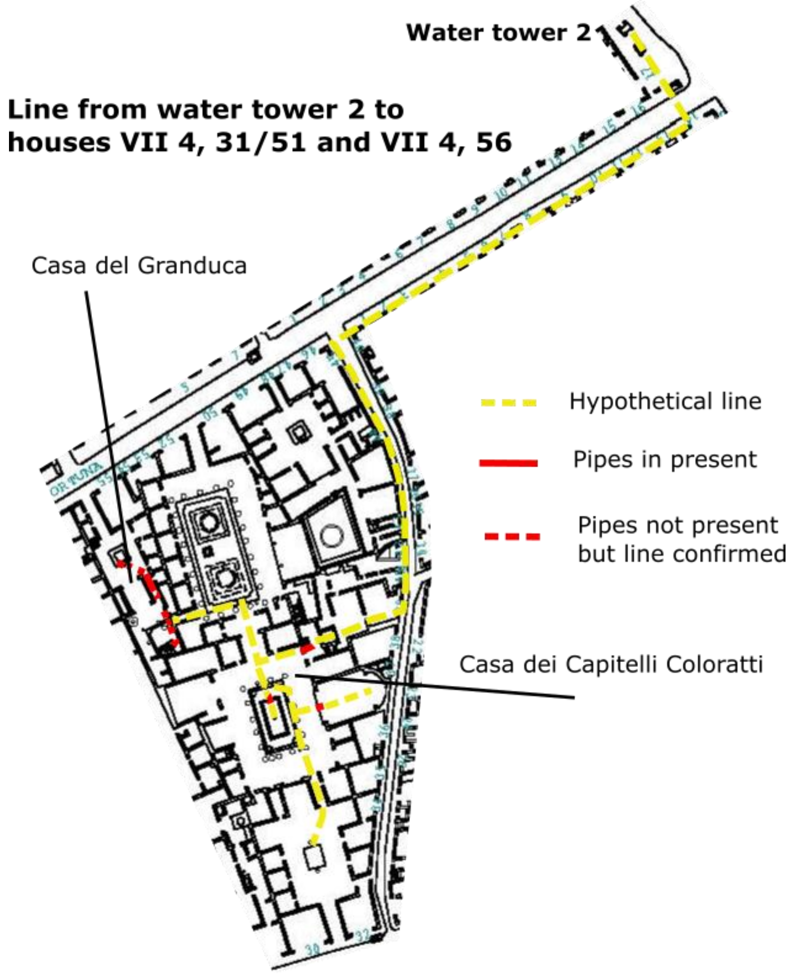

Figure 22. *Line from water tower 2 to VII 4, 31/51 and VII 4, 56. Map by Parco archeologico di Pompeii, modified by author.*

Total to pool in VII 4, 31/51 room 18	Total to threshold in VII 4, 31/ 51 room 31	Total to *aedicule* fountain in VII 4, 56 room 13	Total to *impluvium* in VII 4, 56 room 2
179.08 m	188.08 m	201.24 m	207.4 m

House IX 3, 5/24 Casa di Marcus Lucretius

As has been noted in the previous chapter, the pipeline to this house probably starts from the water tower 3 in the southeast corner of the city block VII 2. It is the closest one to the house. The line could have taken two routes from the tower to the entrance of the house. It could have crossed Via Stabiana immediately to the side of the city block IX 3, turned north along the street and turned right at the entrance to the house. Alternatively, the line could have run at the west side of Via Stabiana and turned right near the entrance to the house and crossed the street at that point. Between these two alternative routes there is no significant difference in length but using the shortest possible distance the first route has one more bend. This could be significant. Bends are potential rupture spots in a pipeline because flow of water gains extra turbulence inside a bend and this will eventually wear down wall of pipe. The problem is magnified by the manufacturing process of pipes. Bending a straight pipe will cause unevenness at the inner surface of a pipe and this will cause even more turbulence. I personally believe that Romans were aware of this fact at least in some level and avoided unnecessary bends most of the time. This assumption is difficult to prove, and beyond the scope of this thesis.

Another interesting question here is where the pipeline actually crossed the street. The basic assumption is that new lines were gradually added to the pipeline grid. If lines crossed streets in random spots this might have caused unnecessary rupture of street traffic due to opening of street pavement. Pavements were made of large and heavy basalt slabs and removing stones, installing pipes and laying stones back on their positions would take a considerable amount of time. All this time street traffic would have been restricted. It is likely that prolonged disruption of traffic was unwanted and *plumbarii* were on some pressure to do their work quickly. How these persons selected a suitable spot and how crossings were done is difficult to discern and worthy of independent research. For example, it is possible that elevated pedestrian crossings could be used to make the pipe crossings. This could be studied comparing locations of elevated pedestrian crossings, locations of water towers and locations of known pipeline connections to the houses.

Considering the two points mentioned above – number of bends and pipeline using pedestrian crossings – route one is more likely. Near the entrance to the house there is a pedestrian crossing, but it is located north from the entrance. Using this in the second possible route would make route longer and it would have one more bend than the first route. Therefore, I think that route one is more likely, and this was used here.

The pipeline could have entered the house either through room 1 or room 3. In neither room there is no direct evidence of the pipeline, but in the façade of room 3 there is a relieving arch (Figure 23). This arch could have diverted the weight of the wall away from the channel underneath it and the pipeline could have entered the house under it. In addition, the pipeline could reach room 17 in a straight line from here. Consequently, I think it is slightly more probable that pipeline entered the house through room 3 and I use this route in the calculations. This has very little effect on the total length of the pipeline, however.

Figure 23. *Entrance to IX 3, 5/24. Relieving arch can be seen in left side of the entrance. Copyright EPUH/ Tiina Tuukkanen*

Pipeline crossed room 3 and entered room 2 (*atrium*) where there is no evidence of pipeline but it is likely that the pipe line ran in a straight line along the northern wall of room 2 and entered room 17 where the first surviving pipes are. In room 2 there is evidence of now lost *impluvium* in the center of the room which could have featured water elements. Therefore, a branch of the pipeline could have run to the center of the room. The rest of the line is presented in chapter 3 and is not presented her. The whole pipeline is presented in Figure 24.

Line to garden in IX 3, 5/24

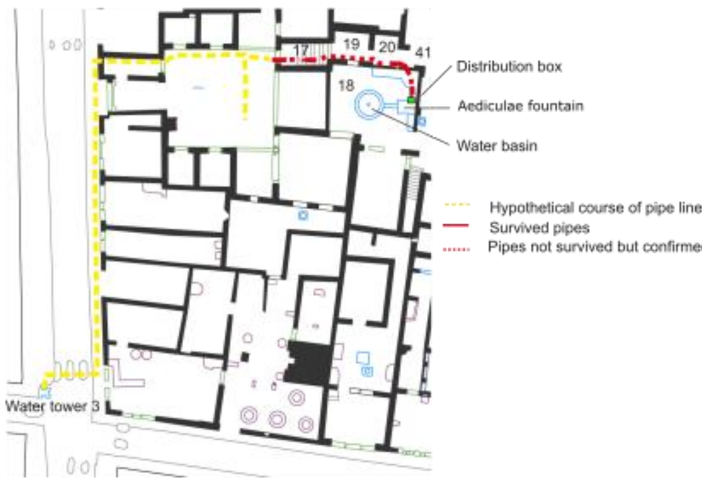

Figure 24. *Map of whole pipeline from water tower to garden in Casa di Marcus Lucretius. Map by Maija Holappa/EPUH, modified by author.*

Measurements using the web-based tool ranged from 62.1 m to 62.9 m and the mean from these is 62.5 m. Manual measurements ranged from 61 m to 64 m and the mean from these is 62.7 m. The mean number from these two results is 62.6 m and this was used as the base length of the pipeline.

To this number height of the water tower 3 should be added. Larsen has given 6.05 m as a height of water tower (Larsen 1982) and Olsson measured height of the tower as 5.96 m (Olsson 2015 Appendix 1 table1) and I use this figure as baseline for height of this tower. The top of the tower has slightly crumpled slightly so I feel that a small correction should be added to the base height of the tower. It is difficult to say without a detailed study exactly what was the height of the tower when it was used, but as both Larsen (1982) and Heres (1994) mention only “some crumbling” I assume that the crumbled part is low i.e. 3–10 cm. In this range any number will probably be reasonable so I will use 4 cm as an added height to tower height presented by Olsson. Consequently, the estimated tower height for water tower 3 is 6.0 meter. This added to the estimated length of pipeline gives 68.6 m as a total length of this pipeline.

Houses IX 3, 18 Taberna di P. Pacci Clari and IX 3, 19-20 Pistrinum di T. Genialis

The most probable route of the pipeline to these two houses is quite straightforward and therefore does not require a very detailed study. The pipeline originated from water tower 3 in the southeastern corner of VII 2. It crossed Via Stabiana immediately, turned south and from the corner of Via Stabiana and Via degli Augustali turned east. Then it continued along

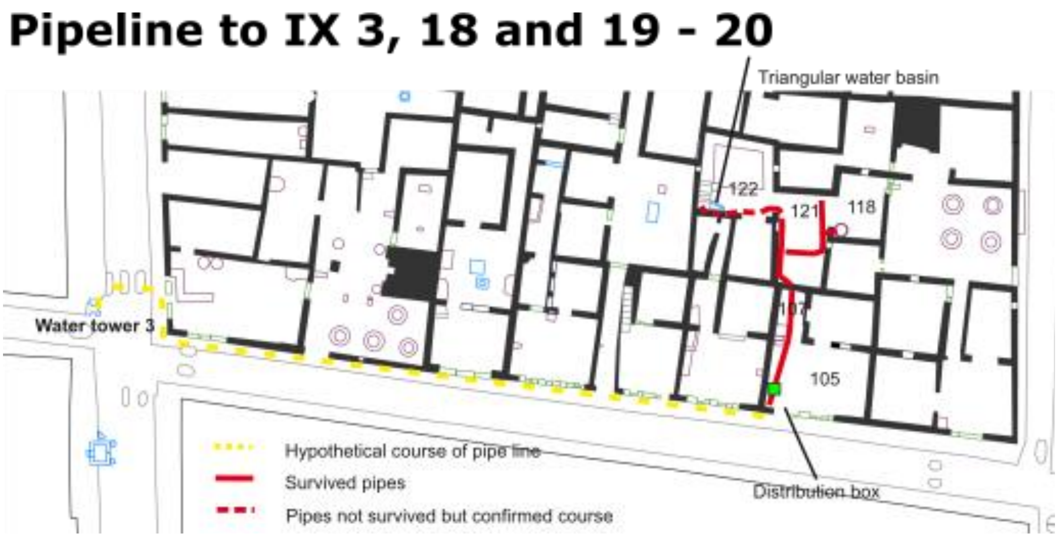

Figure 25. Map of whole pipeline in IX 3, 18 and IX 3, 19-20. Map by Maija Holappa/EPUH, modified by author.

the northern side of the continuation of Via degli Augustali towards the entrance of IX 3, 18 and entered the house through a wall on the western side of the entrance. From there it continued through rooms 105 and 107 to room 121 in house IX 3, 19–20. It is worth noticing that in house IX 3, 18 there is no evidence of piped water usage. This might indicate that this house was owned by the same owner as IX 3, 19–20 at least during the construction of the pipeline. The rest of the line is presented in chapter 3 and is not presented here. The course of the whole line is presented in Figure 25.

The length of the whole line was calculated in a few sections. For a line from the water tower 3 to the wall next to a triangular water pool in the southwestern corner of room 122, the measurements using the web-based tool ranged from 71.4 m to 72.3 m and the mean from these is 71.86 m. Manual measurements ranged from 71.5 m to 72.5 m and the mean from these is 72 m. The final mean length from the two methods is 71.93 m and adding the height of the water tower 3, 6.0 m, gives 77.93 m for a total length of this line.

For the line to room 118 the measurements using the web-based tool ranged from 69.3 m to 70.2 m and the mean from these is 69.5 m. The manual measurements for this line ranged from 67 m to 67.5 m and the mean from these is 67.13 m. The mean from the two methods is 68.32 m and adding height of the water tower 3 gives 74.52 m for the total length of the pipeline.

6 The Physics

Water has three states: solid as ice, liquid as water and gas as vapor or steam. Water has low viscosity. Foreign particles dissolve to water easily and that is why it is often called as universal solvent. Water is practically incompressible which affects greatly its properties. With laws of fluid dynamics aspects of water flow can be described. In this chapter I will give a brief overview of this very complex subject and only from the practical perspective of calculating flow inside pressurized piping systems.

Types of water flow

Water flow can be laminar or turbulent. In laminar flow water flows smoothly. When velocity of the flow increases water starts to whirl and flow changes to turbulent. To determine flow type Reynolds's number is used. It can be calculated using the following equation (Nakayama & Boucher 1999):

$$\boldsymbol{Re = \frac{\rho V D_H}{\mu} = \frac{V D_H}{\upsilon}}$$ where:

$\boldsymbol{\rho}$ = density of water

$\boldsymbol{v}$ = mean velocity

$\boldsymbol{D_H}$ = hydraulic diameter

$\boldsymbol{\mu}$ = dynamic viscosity of water

$\boldsymbol{\nu}$ = kinematic viscosity of water

Density and viscosity of water are dependent on temperature so an arbitrary temperature of 20℃ will be used in this work if needed. This temperature is often used in theoretical flow calculations because both density and viscosity of water are close to round numbers in this temperature. This was desirable when calculations were made manually, but thanks to modern computers this is not necessary anymore. The practice continues though. In this temperature viscosity is 0.001005 Pa·s (Pascal second) and density is 998.2071 kg/m^3. Kinematic viscosity is dependent of dynamic viscosity and can be expressed as $\boldsymbol{\nu = \mu/\rho}$. Flow is laminar when Re < 2300, transitional when 2300 < Re < 4000 and turbulent when Re >

4000 (Nakayama & Boucher 1999 p. 46). Type of flow affects used calculations. In practice most flows are turbulent.

Flow inside a pipe is rather complex process and formulas that describe them are often generalizations. Flow inside a pipe consists of several layers of different velocities. Fastest velocity is in the middle of a conduit and velocity in the layer closest to the surface of conduit is very close to zero (Nakayama & Boucher 1999, 102; Mustonen 1973, 87). In this layer incrustations form.

Bernoulli's principle

Water can have potential energy (water level) and kinetic energy (velocity) (Nakayama & Boucher 1999). According to the physical law of conservation of energy, in closed system total energy cannot change. So, an increase in velocity decreases pressure and vice versa. In fluid dynamics this is called Bernoulli's principle and it is often presented as the following equation (Li & Lam 1964, 81):

$$\frac{p}{\rho} + gh + \frac{Q^2}{2} = constant$$ where:

ρ = density of water (kg/m^3)

p = pressure

g = acceleration by gravity on Earth (m/s^2)

h = elevation (m)

Q = velocity (m/s)

This equation assumes steady, incompressible and frictionless flow. Every part of the equation represents energy. Energy loss by friction can be estimated with Darcy–Weisbach equation.

Hydraulic perimeter

Hydraulic perimeter is a concept, which is used when the pipe is irregular. This is a case with Roman water pipes as we have seen above. Equation for calculating hydraulic perimeter is:

$$D_H = \frac{4A}{P}$$ where:

D_H = hydraulic perimeter

A = cross sectional area (m^2)

P = wetted area i.e. area that is in connection with water

In modern times pipes are usually round and most of the handbooks reflect this in their usage of formulas, but hydraulic perimeter can be used in flow calculations when area is called in formula.

Continuity equation

The law of conservation of mass is in effect with pipe flow too. It is called continuity equation in fluid dynamics and is often stated as following (Nakayama & Boucher 1999, 55):

$$Q = vA$$ where:

Q = volumetric flow or discharge as it is referenced in some publications (m^3/s)

v = velocity (m/s)

A = area (m^2)

Continuity equation assumes steady flow. It states that in a system the rate of mass entering the system is the same as the rate of mass leaving the system. It also states that **Q** is constant and if **v** increases **A** decreases i.e. when pipe narrows velocity increases (Nakayama & Boucher 1999, 56). This equation represents mass.

Velocity

Velocity is a movement of water inside of pipe and it consists of elements of speed and direction. The only way to calculate velocity in this particular case is with the following equation. It is called **Torricelli's theorem** and it is a special case of Bernoulli's principle.

Result is a theoretical mean velocity of flow in given point of flow (Nakayama & Boucher 1999, 67):

$\boldsymbol{v} = \sqrt{2gh}$ where:

$\boldsymbol{v}$ = mean velocity (m/s)

$\boldsymbol{g}$ = acceleration by gravity on Earth (m/s^2)

$\boldsymbol{h}$ = water head (m)

This equation does not take into account friction, which can affect velocity considerably. Acceleration by gravity on Earth is a constant that is slightly governed by elevation. Exact figure at sea level is 9.80665 m/s^2, but in practise a rounded figure 9.81 m/s^2 is often used in manual calculations. Rate of acceleration increases very slowly, and Pompeii is close to sea level so, above-mentioned figure is used in this work.

Water head is a height of water column inside a pipe system and is only governed by the elevation difference between two points. It is calculated simply by subtracting elevation level of pipeline's origin i.e. level of water in water tank on top of the water tower and elevation level of given location of a pipe. Result is height of water column in meters inside piping system.

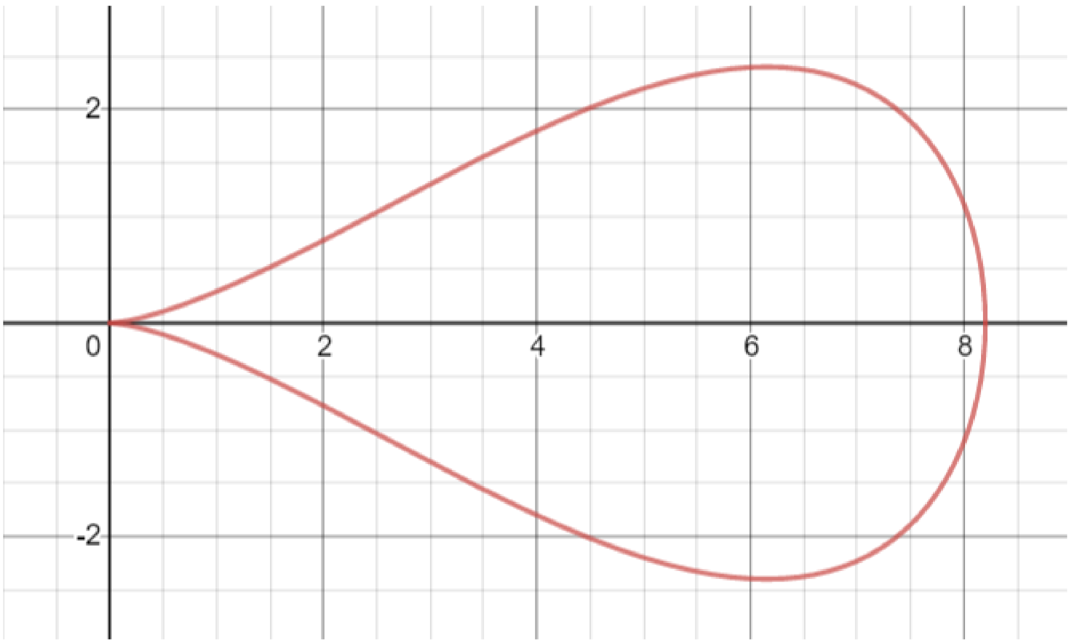

Figure 26. *Graph of Pear-shaped quartic. This particular case refers to pipe in V 1, 28 room b where **a** is 8.2 and **b** is 9.1. Graph was made using graphical calculator at* https://www.desmos.com/calculator.

Pear- shaped quartic

Graph of Pear-shaped quartic is a graphical representation of the Cartesian equation

$$\boldsymbol{b^2y^2 = x^3(a\text{-}x)}$$

This curve is counted among one of the famous curves in mathematics. Shape of the curve from this equation is an approximation for a typical Roman pipe shape. This is not the only equation which curve resembles shape of Roman pipe ex. Mandelbrot lemniscate of second degree gives more rounded shape and Piriform curve gives more bulbous lower region. However, Pear-shaped quartic was chosen because vertical diameter can be inserted straight into the equation as **a**. Area of this curve can be calculated from equation

$$\boldsymbol{A = \frac{a^3\pi}{8b}}$$

Length of a perimeter, which is needed in pressure loss calculations, can be obtained from a simplified Cartesian equation by integration. Simplifying equation of Pear-shaped quartic by using basic algebra we got $\boldsymbol{y = \sqrt{\frac{x^3(x-a)}{b^2}}}$.

Summary

As we can see from above, two crucial pieces of data are needed for water flow calculations. First is the elevation difference between a chosen point in a pipe line and last known point where water was in touch with the atmosphere. The second required piece of information is the inner diameter of the pipe. Elevation difference is needed to get water head and diameter is needed to get perimeter and area. Both of these are available in the existing archaeological documentation and publications. Accuracy of data is not always on a desired level though. This lack of accuracy is prevalent especially with the data on pipe dimensions. Often publications have omitted pipe dimensions altogether or only one diameter is present, or data is rounded to the nearest whole number or dimensions were from the outer diameter. All this might be related to difficulties to document pipe dimensions or is simply an oversight. Nevertheless, these can still be used but the accuracy of the results suffers. Water towers are generally speaking well documented and data is readily available. This includes crucial elevation data, and these are reliable. In contrast, the elevation data of pipe locations are scarce. Often the best available data is some distance away and results suffers because of that.

The simplest way to do calculations in this case is to use Torricelli's theorem to get mean velocity and use that in the continuity equation to get flow rate. Both of these equations omit friction losses. I tried to calculate major loss from length of pipeline, but results were unusable. Reason for this is that Torricelli's theorem already contains pressure differences. Pear-shaped quartic turned out to be a reasonable proxy for Roman pipe shape.

7 The calculations and the results

Data needed to calculate volumetric flow rate inside a pressurized pipe have been demonstrated above but short reminder is presented here in a list form:

- Physical dimensions of pipe
- Elevation data of pipe location
- Elevation data of corresponding water tower

Several equations were used to obtain results: equations for pear-shaped quartic to get perimeter and area of non-round pipes, basic equations for circle to get perimeter and area of pipes where only one dimension was available, Torricelli's theorem to get mean velocity in pipe location, and continuity equation to get volumetric flow rate of pipe flow.

First step was to get perimeter for pipes. Pipes, where only one dimension was available, were simply calculated using equations for circle. When the diameter of the circle is known equation for perimeter is $\boldsymbol{p} = \boldsymbol{\pi d}$ where $\boldsymbol{p}$ is perimeter and $\boldsymbol{d}$ is the diameter. When the diameter of the circle is known equation for area of the circle is $\boldsymbol{A} = \frac{\boldsymbol{\pi}}{\mathbf{4}}\boldsymbol{d}^{\mathbf{2}}$ where $\boldsymbol{A}$ is area and $\boldsymbol{d}$ is the diameter.

Equations for non-round pipes were more complicated. As mentioned before, pear-shaped quartic was chosen for calculations because its graph resembles the shape of Roman pipes and vertical diameter can be inserted straight into the equation as **a**. Before perimeter could be calculated, the equation needed to be simplified using basic rules of algebra. This was needed because integrating multivariate equations gives area under the curve and not perimeter. Perimeter can be gotten from univariate equation. So, from equation $\boldsymbol{b}^{\mathbf{2}}\boldsymbol{y}^{\mathbf{2}} = \boldsymbol{x}^{\mathbf{3}}(\boldsymbol{x}-\boldsymbol{a})$ we got $\boldsymbol{y} = \sqrt{\frac{\boldsymbol{x}^{\mathbf{3}}(\boldsymbol{x}-\boldsymbol{a})}{\boldsymbol{b}^{\mathbf{2}}}}$. Integrating this equation is time consuming and complex task so to simplify this process WolframAlpha's on-line Arc Length Calculator[4] was used. The other thing that needed to be done before actual calculations were getting values of $\boldsymbol{b}$ for above-mentioned equations. Values of $\boldsymbol{a}$, as mentioned, were vertical diameters of the pipes. This was done on-line using Desmos's graphic calculator where interactive graph for pear-

[4] https://www.wolframalpha.com/examples/mathematics/calculus-and-analysis/applications-of-calculus/arc-length/.

shaped quartic were found made by Dr. Co Hong Tran[5]. Vertical diameter was inserted in graph as $\boldsymbol{a}$ and then $\boldsymbol{b}$ was manually determined. Graph is drawn from origin so that half of the curve is above x-axel and half is below x-axel. To find the value of $\boldsymbol{b}$ different values were tried until longest diameter of the graph in y-axel was same than horizontal diameter of the pipe and this value of $\boldsymbol{b}$ was recorded. After this, values of $\boldsymbol{a}$'s and $\boldsymbol{b}$'s were inserted to simplified equation from above and whole equation was inserted to Arc Length Calculator. Result from calculator was recorded. This result was only half of the length of a curve, but since both sides of the curve are identical, result needed only to be multiplied by two to get the perimeter. Area of the pear-shaped quartic is

$$\boldsymbol{A = \frac{a^3\pi}{8b}}.$$

Elevation points of the pipes were obtained from respective documentations. In cases where elevation was not known, the nearest elevation point from RICA maps was used. These were available in web site of Pompeii Bibliography and Mapping Project which can be accessed here http://digitalhumanities.umass.edu/pbmp/?page_id=1258. Estimated elevation data of respective water towers were obtained from Olsson 2015 Appendix 1 table 1. Elevation of pipe was subtracted from elevation of tower and the result was used as water head $\boldsymbol{h}$.

Torricelli's theorem $\boldsymbol{V = \sqrt{2gh}}$ was used to get mean velocity of water flow in chosen point. In this equation $\boldsymbol{g}$ is acceleration by gravity on Earth at sea level which is, as we have seen before, 9.80665 m/s^2. Continuity equation $\boldsymbol{Q = VA}$ was used to get volumetric flow rate.

All this data along with data of pipe locations was then inserted into two Excel sheets: one for non-round pipes and one for pipes with one dimension known. Appropriate formulas were made in both sheets to make calculations. Finally, correct unit conversions were made so that final results could be presented as litres per second. Full results can be found in tables at Appendix 2.

Representative sample of results, which have been rounded to hundredths, are shown in tables below. Red numbers in tables refers to red numbers in corresponding maps in this

[5] https://www.desmos.com/calculator/es2fstgpcc

section. These maps show the pipelines, locations of the pipes where calculations were made and the same results than in the tables below (Figures 27–29).

Table for results from city block V 1

V 1, 7 Room I (culina) Westward pipe from southern box	1	30.56 l/s
V 1,7 Room I (*culina*) pipe in the stairs to kitchen	2	4.77 l/s
V 1,7 Room h	3	2.96 l/s
V 1,7 Room b (peristyle) Large pipe to large distribution box from west	4	20.54 l/s
V 1,7 Room b (peristyle) Northern pipe from small distribution box feeding aediculae fountains	5	8.99 l/s
V 1,7 Room b (peristyle) Pipes on top of the parapet wall (jets)	6	1.00 l/s
V 1,7 Room b (peristyle) Pipe leading to the eastern porticoe	7	3.73 l/s
V 1,7 Room 10 (corridor) Pipe in northern part of corridor	8	11.05 l/s
V 1, 28 Room b	9	23.33 l/s

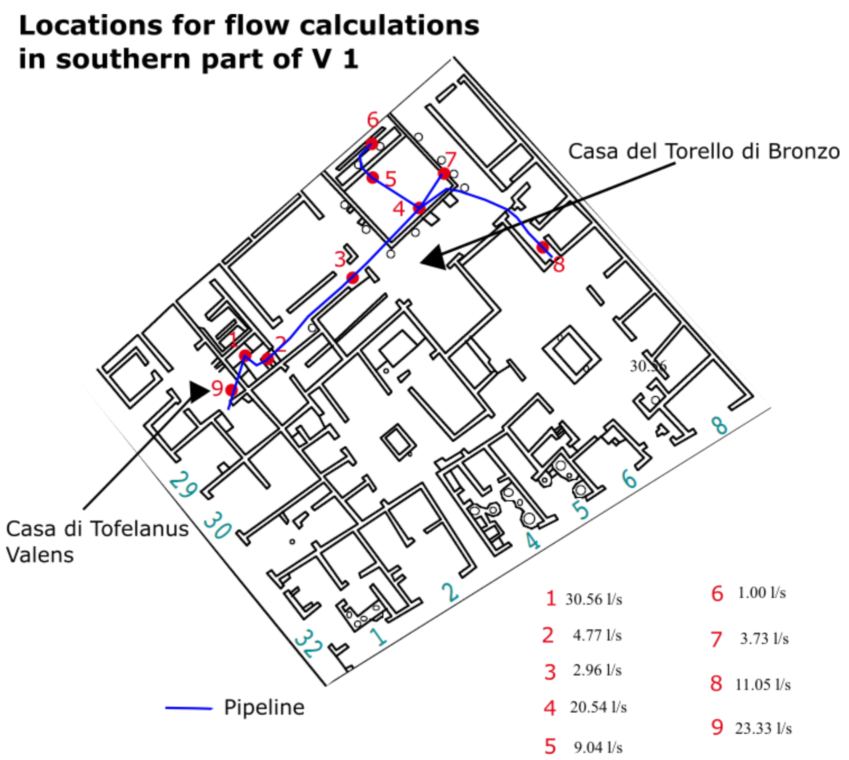

Figure 27. *Map of city block V 1 with points of calculations. Map by Parco archeologico di Pompeii, modified by author.*

Table for results in city block VII 4

VII 4, 31/51 Room 58 Pipe under the stairs	3	50.76 l/s

VII 4, 31/51 Room 18 (peristyle) Pipe in wall of the pool	2	50.76 l/s
VII 4, 31/51 Room 18 (peristyle) Pipe under threshold to room 31	1	19.83 l/s
VII 4, 56 Room 2 (*atrium*) Pipe inside ceramic pipe	4	8.73 l/s
VII 4, 56 Room 11	5	4.96 l/s
VII 4, 56 Room 13 (peristyle) Pipe in eastern wall at the height of 43 cm	6	1.78 l/s

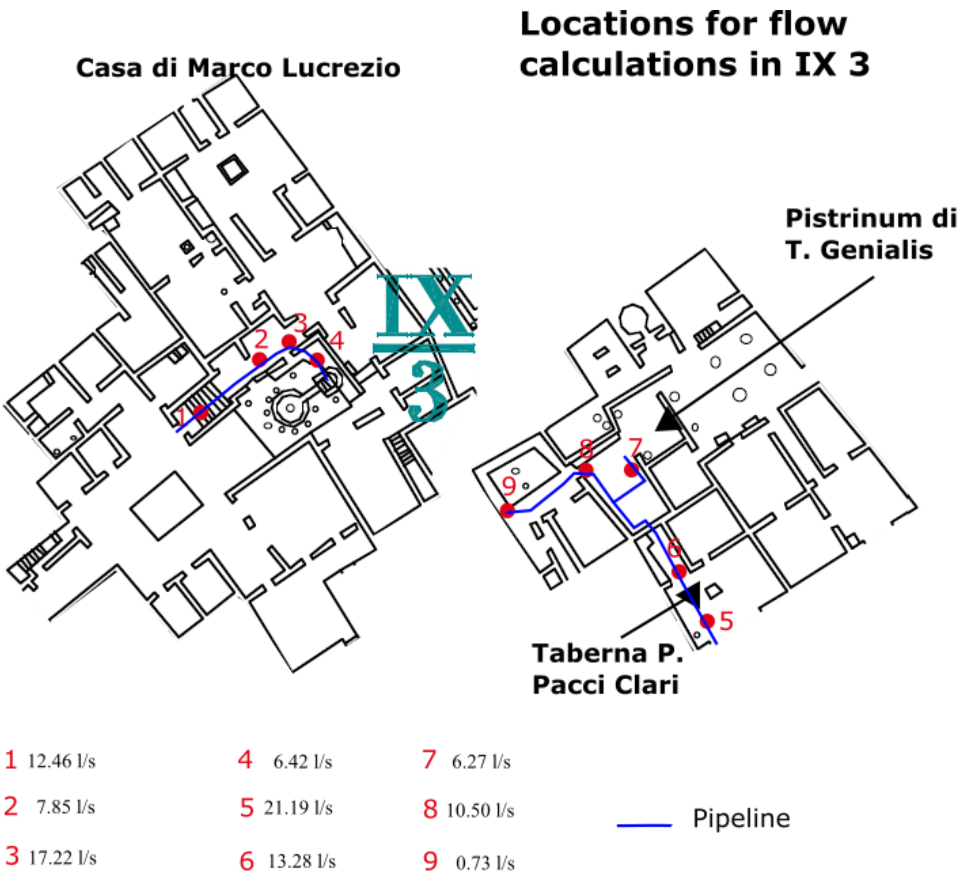

Figure 29. *Map of city block IX 3 with points of calculations. Map by Parco archeologico di Pompeii, modified by author.*

Table for results in city block IX 3

IX 3, 5/24 Room 17 (stairs) Pipe in threshold	1	12.46 l/s
IX 3, 5/24 Room 20 (corridor)	2	7.85 l/s
IX 3, 5/24 Room 41	3	17.22 l/s
IX 3, 5/24 Room 18 (garden) Pipe entering room	4	6.42 l/s

IX 3, 18 Room 105	5	21.19 l/s
IX 3, 18 Room 107 at threshold	6	13.28 l/s
IX 3, 19–20 Room 121 Pipe at the threshold to room 122	8	10.50 l/s
IX 3, 19–20 Room 121 Pipe from second branching towards north	7	6.27 l/s
IX 3, 19–20 Room 122 Pipe visible at the height of c. 60 cm which is added to asl of room floor 31.19	9	0.73 l/s

Out of curiosity, I also calculated theoretical flow rate for three large pipes that started from the *castellum aquae*. Dimensions for these, or to be more precise dimensions for openings where pipes were situated, are mentioned in several publications (Ohlig 2001; Olsson 2015). These are c. 30 cm for central opening and c. 25 cm for both side openings. Elevation for middle pipe according to Ollsson is 43.0 m and for side pipes 42.6 m (Olsson 2015, 29). This number was used as a higher elevation point. I chose two numbers as a lower elevation point: 42.0 m and ten centimetres below each pipe. These numbers are purely arbitrary, but these elevation points are in the near vicinity of *Castellum aquae* and I wanted to see how much water flowed out of the reservoir. I chose 2.5 cm as a thickness of pipe wall and subtracted that from sizes of openings. Results are presented in separate table in this section. I must stress that these results are very theoretical, but they might be useful

Table for results for *castellum aquae*

Castellum aquae middle pipe	263.05 l/s at 42.0 m	83.18 l/s at 42.9 m
Castellum aquae right pipe	136.40 l/s at 42.0 m	55.68 l/s at 42.5 m
Castellum aquae left pipe	136.40 l/s at 42.0 m	55.68 l/s at 42.5 m

The results from the city block V 1 show an interesting tendency. In the beginning of the line the volume of the water is large, over 22 l/s. This is as expected since this house had numerous water features and consequently needed large amounts of water. The largest amount of water was needed in the garden and a pipe with the 6.3 cm diameter leaving from the southern box of double distribution in room l reflects this. This pipe most likely ran to the garden. The result for this pipe, 30.56 l/s, is larger than the pipe feeding the double distribution box. Probable reason for this is that there is only one dimension presented for this pipe. From here on we can see a clear descending trend. The results get smaller for each consequent pipeline and I think that the results reflect importance of the different water features to the owner of the house. The results from points two and three are too small that these pipes could have been the main line to the garden. The result for a jet on top of the parapet wall is for one jet only. The result for the point eight shows a moderate amount of water going to the southern *atrium*.

The results from the city block VII 4 are somewhat similar to the previous ones as a very large amount of water entered the house VII 4, 31/51. This is not a surprise since a pipe with a diameter of 8 cm seems to be large for a private house. The same amount of water entered the *viridarium* in room 18 maybe causing an overflow unless flow was interrupted in some way. The result from the point one is on the same level than the results from the main line in V 1, 7, but this probably reflects the inaccuracy of the data rather than actual flow rates. The results for the house VII 4, 56 are very modest compared to the results from VII 4, 31/51. The pipe that supplied water to the entire house VII 4, 56 conducted less water than what was delivered to the *atrium* of its neighbour. The result from the point six is for the water jet on top of the base in the basin.

The results are for the city block IX 3 are interesting. They seem to indicate that the commercial premises in the southeastern corner of the city block were more important recipients of piped water than the luxury house of the city block, IX 3, 5/24 which seemed to receive only a modest amount of water. The difference between the results from rooms 20 and 41 in the house IX 3, 5/24 can be explained by inaccuracies in known data.

Problems and discussion

All these results are theoretical volumetric flow rates. In reality flow rates were smaller, in some cases considerably so. Main reason for this is that none of the used formulas did consider various pressure losses that occur in pipes. Most important cause for pressure loss is friction. Leak is also a pressure loss but that cannot be calculated. Friction happens when water is in touch with an inner surface of a pipe and it slows down movement of water and causes loss of energy in flow. There are two types of pressure losses: major loss, which considers only a length of the pipe, and minor losses, which happen in various pipeline features like bends, taps and distribution boxes. Effects of these could be considerable to flow rate. Pressure losses can be calculated, but in order to do that we would need to know data that we do not have, mainly velocity or size of a pipe leaving a tank. Torricelli's theorem can be used to get velocity, but it already contains pressure changes in form of head **h** and pressure loss calculations using velocity gotten through Torricelli's theorem would give wildly wrong results. Hagen–Poiseuille equation could be used if we knew size of a pipe leaving the tank on top of a water tower. Nevertheless, I believe that the results presented here are useful and can be used to get a better picture of Roman water use.

There are also problems with the archaeological documentations and with the published data. These problems can be divided into two categories: problems of technical nature and problems of editorial nature. The technical problems are related to the difficulties to record the pipes accurately in archaeological context. It could be difficult or impossible to record for example the width of the pipe wall or the horizontal dimension. These kinds of problems are easy to understand and in these cases an archaeologist should simply record what he, she or they can as accurately as possible according to the principles of good archaeological practises. Partial information can lead to the inaccurate results in pipe flow calculations. Good example of these kind of problems can be seen above in results from pipes in rooms 20 and 41 of the house of IX 3, 5/24. We can see from the context that they part of the same pipeline in a same elevation level, of approximately the same size and we could reasonably expect that the results reflect these facts, but the calculated results are very different, 7.85 l/s in room 20 and 17.22 l/s in room 41. Reason for this is that the pipe in the room 20 has recorded dimensions of 3-5 cm and the pipe in the room 41 has recorded dimension of 5 cm. This discrepancy illustrates well the need for an accurate recording of pipe dimensions. The editorial problems are of a different nature. If an archaeologist finds a pipe *in situ* and choose not to record it that is an editorial problem. Same is true if he, she or they choose not to publish data in some form be it in publication or in supplements of some kind. Consequently, I wish to encourage researchers to gather the pipe dimensions and publish them by showing what can be done with the information they have gathered.

In order to get more accurate results several feasible lines of research could be taken. Most accurate of these is replicating part of a Roman pipeline and conduct experiments with it. This line of research would include manufacturing pipes, joining them into a working pipeline system and doing various experiments related to pressure and flow rate. Manufacturing Roman pipes would certainly give deeper insight in to a manufacture process. Same would be true for joining practises. In fluid mechanics, the most accurate method to get flow rates is by experimenting. Equations that describe the laws of fluid mechanics are mostly experimental and they contain approximations and inaccuracies. They are very useful in engineering, but the most accurate way to get velocity and flow rate would be to observe and measure flow through a piping system. Another line of research is related to shape of pipes. I believe that pear-shaped quartic is a useful proxy for Roman pipe shape and is more accurate than using round shape, but it is certainly possible that there exist more accurate formulae. Developing easy-to-use method for archaeologists to record pipes more accurately in archaeological context might be feasible. More published data about pipe dimensions and elevation levels would also be most useful.

8 Conclusions

In this work I have shown that volumetric flow calculations based on surviving archaeological remains in Pompeii could be done if suitable data is available. Needed archaeological data are pipe dimensions and elevation data of pipe locations and water towers. I have shown physical equations to do the calculations. Most important of these are Torricelli's theorem and continuity equation in addition of formulas for circle and pear-shaped quartic. I presented pear-shaped quartic as a useful proxy for shape of Roman water pipe and showed how to use it for perimeter and area of Roman pipes. I gave a short overview of Roman literary sources and previous research relevant to this work. I also gave an overview of water system in Pompeii and commented various aspects of it. In archaeological section of my work I described vetting process for choosing suitable city blocks and houses for calculations. I deemed city blocks V 1, IX 3 and two houses – VII 4, 31/51 and VII 4, 56 – in city block VII 4 to be suitable study cases. I presented short overview of each city block and house and gave more detailed descriptions of rooms where water pipes were found. I presented measurements of pipes, taps and distribution boxes in each room and gave available elevation level data. I made some comments and observations along the way about various subjects. I also described four water towers – towers number 1,2,3 and 7 – related to study cases. I presented possible pipelines from water towers to points to water usage, measured lengths of these lines and presented received results. I made calculations, described calculation process and presented results. In the end, I discussed about problems in flow calculations and made some recommendations for possible future research.

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Appendix 1

House V 1, 7 Casa del Torrello di Bronzo

(all figures from Staub 2013 except asl which was taken from nearest elevation point in RICA maps)

Room l: *Culina* (kitchen) asl 34.8

Northern box: diameter: 10-150 mm length: 255 mm

Southern box: diameter: 180 mm length: 270 mm

Westward pipe from southern box: diameter 63 mm

Tap: diameter of upper closure: 55 mm

Westward pipe from northern box: diameter 45 – 55 mm

Eastward pipe from northern box: diameter 37 mm

Tap: diameter of upper closure: 30 mm

SE-headed pipe from northern box: diameter 21 – 26 mm

Tap: diameter of upper closure: 30 mm

SE-headed pipe from southern box: diameter 20 – 24 mm

Tap: diameter of upper closure: 33 mm height: 96 mm

Northward pipe from southern box: diameter 30 – 35 mm

Tap: diameter of upper closure: 30 mm height: 90 mm

Pipe in the stairs to kitchen: ext. diameter: 25 – 35 mm

Room h: asl 34.8

ext. diameter: 30 – 35 mm

int. diameter: 20 – 25 mm

Room b: Peristyle asl 34.8 (RICA maps have an elevation point in this room)

Large distribution box: diameter: lower part 290 mm height: 225 mm

upper part 140 mm height:65 mm

Pipes emerging from large distribution box:

Pipe towards small distribution box: ext. diameter: 36 – 46 mm

Pipe with tap towards small basin: ext. diameter: 33 mm

Tap: diameter of upper closure: 35 mm

ext. diameter of tap-pipe: 22 mm

Pipe with tap and enlargement towards NE: ext. diameter: 28 mm

ext. diameter of enlargement: 38 mm

Tap: diameter of upper closure: 34 mm height: 98 mm

ext. diameter of tap-pipe: 19 mm

Pipe towards east: ext. diameter: 28 mm

Pipe with tap towards east: ext. diameter: 29 mm

Tap: diameter of upper closure: 74 mm

ext. diameter of tap-pipe: 39 mm

Pipe with tap towards SE: ext. diameter: 44 mm

Tap: diameter of upper closure: 48 mm

ext. diameter of tap-pipe: 23 mm

Pipe with tap from upper part of the box to W: ext. diameter: 36 – 45 mm

Tap: diameter of upper closure: 28 mm

ext. diameter of tap-pipe: 16 mm

Large pipe towards west: ext. diameter: 55 – 63 mm

Small distribution box: diameter: 90 mm length: 220 mm

Pipes emerging from small distribution box:

Pipe from large distribution box: ext. diameter: 30 – 40 mm

Southern pipe feeding jets on parapet wall: ext. diameter: 34 – 45 mm

Tap: int. diameter of drum: 32 mm height: 92 mm

ext. diameter of bronze pipe: 34 – 39 mm length: 180 mm

Northern pipe feeding *aediculae* fountains: ext. diameter: 33 – 46 mm

Tap: int. diameter of drum: 28 mm height: 105 mm

ext. diameter of bronze pipe: 30 – 35 mm length 170 mm

Main pipe feeding western *porticoe*: ext. diameter: 32 – 42 mm

int. diameter: 22 – 26 mm

Southern pipe: ext. diameter: 24 – 32 mm

int. diameter: 12 – 17 mm

Northern pipe: measurements not possible

Pipes on top of the parapet wall (jets): ext. diameter (average): 20 – 21 mm

int. diameter (average): 12 – 14 mm

Pipe leading to now lost pipe with tap at the eastern porticoe:

ext. diameter: 28 – 47 mm

int. diameter: 21 – 30 mm

Pipe leading to fountains in southern portico:

first part: ext. diameter: 30 – 36 mm

		int. diameter: 13 – 20 mm
	second part:	ext. diameter: 31 – 36 mm
		int. diameter: 20 – 24 mm

Room 10: Corridor

Pipe in northern part of corridor:	ext. diameter: 38 – 49 mm	
Pipe at the door to south:	ext. diameter: 41 – 55 mm	
	int. diameter: 28 – 42 mm	

House V 1, 28 Casa di Tofelanus Valens

Room b:	Diameter: 48 – 82 mm	asl 34.8

House VII 4, 31/ 51 Casa dei Capitelli Colorati

(all figures from Sear 2006 except asl which was taken from nearest elevation point in RICA maps)

Room 18: *Peristyle*	asl 34.5 m
Pipe in wall of *viridarium*	Diameter c. 8 cm
Pipe in threshold to room 31	Diameter c. 5 cm
Room 58:	asl 34.5 m
Pipe under the stairs	Diameter c. 8 cm

House VII 4, 56 Casa del Granduca

(all figures from Sear 2004 except asl which was taken from nearest elevation point in RICA maps)

Room 2: *Atrium*	asl 34.5 m
Pipe inside of ceramic pipe	Diameter 3.5 cm
Room 11: Corridor	asl 34.5 m

Ext. diameter 3.5 cm int. diameter 2.5 cm

Room 13: Peristyle asl 34.5 m

Pipe visible at height of 43 cm in eastern wall Ext. diameter 3.5 cm int. diameter 1.5 cm

Pipe on top of base inside basin Ext. diameter 3.5 cm int. diameter 2.5 cm

House IX 3, 5/24 Casa di Marcus Lucretius

(Data from documentations of EPUH)

Room 17: Stairs

Pipe in threshold: Diameter 4 – 6 cm asl. 30.60 m

Pipe in stairs: Diameter 4 – 5 cm asl. 30.76 m

Room 18: Garden

Distribution box: Width: 17 cm Height: 17 cm Height: 34 cm asl: 32.20 m (of room)

Pipe entering room:	Diameter: 3 – 4 cm	Length: 75 cm
Southward pipe from box:	Diameter: 2 cm	Length: 5 cm
Westward pipe from box:	Diameter: 3 – 4 cm	Length: 100 cm
Top pipe in basin:	Diameter 5 cm	Length: 28 cm
Bottom pipe in basin:	Diameter: 5 cm	Length: 33 cm

Room 20: Corridor

Diameter: 3 – 5 cm Length: 79 cm asl: 32.38 m

Room 41:

Diameter: 5 cm Length: 130 cm asl: 32.38 m

House IX 3, 18 Taberna P. Pacci Clari

(Data from documentations of EPUH)

Room 105:

Distribution box Diameter: 13 cm Length: 15 cm Height: 14 cm

Pipeline Diameter: 5 cm Length: 479 cm asl: 30.26 – 30.34 m

Room 107:

Pipe in threshold from room 105 Diameter: 4 cm Length: 100 cm asl: 30.51 m

Pipe near north wall (data from "Pistrina: les boulangeries de l'Italie romaine")
Diameter: 4.2 -5.3 cm asl: 30.51 m

House IX 3, 19–20 Pistrinum di T. Genialis

(Data from documentations of EPUH except room 121 which is from French project "Pistrina: les boulangeries de l'Italie romaine")

Room 121

Pipe at the threshold between rooms 121 and 122

Horizontal diameter 3.6-3.7 cm Vertical diameter 4.8 cm

Pipe 65 cm after the threshold

Horizontal diameter 3.4 cm Vertical diameter 4.4 cm

Pipe near west wall between threshold and the first branching

Horizontal diameter 3.5-3.9 cm Vertical diameter 4.6 cm

Pipe from first branching towards center of the room

Horizontal diameter 3.0 cm Vertical diameter c. 3.5 cm

Pipe from first branching towards south wall

Horizontal diameter 3.9 cm Vertical diameter c. 5.0 cm

Pipe in center of room before pipe joint

Horizontal diameter 2.8 cm Vertical diameter c. 3.6 cm

Pipe near east wall between the pipe joint and second branching

Vertical diameter 2.9-3.1 cm Vertical diameter 3.5 cm

Pipe from second branching towards North

Horizontal diameter 3.7 cm Vertical diameter 4.4 cm

Pipe near the south wall

Horizontal diameter 4.3 cm Vertical diameter 5.3 cm

Elevation of the room is not known so elevation of room 122 is used asl: 31.19 m

Room 122: asl 31.19 m

Pipe visible in wall at the height of 60 cm Diameter 1 cm

Appendix 2.

Pipes with two known dimensions

Location	VerDiam	HorDiam	b	HalfPeri	Perimeter	Area	asl of pipe	asl of tow	Head	Velocity	VolFlowRa	Litre/s
V 1,7 Room I (*culina*) westward pipe from northern box	5.5	4.5	4.366	7.68413	15.36826	14.96457	34.8	39.7	4.9	980.3324	14670.25282	14.670253
V 1,7 Room I (*culina*) SE-headed pipe from northern box	2.2	2.1	2.09	3.614063	7.228127	2.000698	34.8	39.7	4.9	980.3324	1961.349629	1.9613496
V 1,7 Room I (*culina*) SE-headed pipe from southern box	2.4	2	1.87	3.378868	6.757736	2.903033	34.8	39.7	4.9	980.3324	2845.937642	2.8459376
V 1,7 Room I (*culina*) northward pipe from southern box	3.5	3	2.65	4.987294	9.974588	6.353575	34.8	39.7	4.9	980.3324	6228.615475	6.2286155
V 1,7 Room I (*culina*) pipe in the stairs to kitchen	3.5	2.5	3.454	4.514554	9.029108	4.87463	34.8	39.7	4.9	980.3324	4778.758254	4.7787583
V 1,7 Room h	2.5	2	2.03	3.461028	6.922055	3.022622	34.8	39.7	4.9	980.3324	2963.174649	2.9631746
V 1,7 Room b (peristyle) Pipe from large distribution box to small distrbution box	4.6	3.6	3.82	6.312112	12.62422	10.00622	34.8	39.7	4.9	980.3324	9809.421441	9.8094214
V 1,7 Room b (peristyle) Pipe with tap from upper part of the large distribution box to W	4.5	3.6	3.65	6.232574	12.46515	9.804028	34.8	39.7	4.9	980.3324	9611.207162	9.6112072
V 1,7 Room b (peristyle) Large pipe to large distribution box from west	6.3	5.5	4.687	9.045086	18.09017	20.95012	34.8	39.7	4.9	980.3324	20538.08544	20.538085

V 1,7 Room b (peristyle) Pipe to small distribution box from large distribution box	4	3	3.47	5.397954	10.79591	7.242865	34.8	39.7	4.9	980.3324	7100.415453	7.1004155
V 1,7 Room b (peristyle) Southern pipe from small distribution box feeding jets on parapet wall	4.5	3.4	3.88	6.086616	12.17323	9.222862	34.8	39.7	4.9	980.3324	9041.470655	9.0414707
V 1,7 Room b (peristyle) Northern pipe from small distribution box feeding aediculae fountains	4.6	3.3	4.17	6.10852	12.21704	9.166369	34.8	39.7	4.9	980.3324	8986.088706	8.9860887
V 1,7 Room b (peristyle) Bronze pipe from small distribution box	3.5	3	2.65	4.987294	9.974588	6.353575	34.8	39.7	4.9	980.3324	6228.615475	6.2286155
V 1,7 Room b (peristyle) Main pipe from small distribution box feeding western porticoe	2.6	2.2	2	3.680104	7.360208	3.45104	34.8	39.7	4.9	980.3324	3383.166015	3.383166
V 1,7 Room b (peristyle) Southern pipe from small distribution box	1.7	1.2	1.57	2.242674	4.485348	1.228873	34.8	39.7	4.9	980.3324	1204.704057	1.2047041
V 1,7 Room b (peristyle) Pipes on top of the parapet wall (jets)	1.4	1.2	1.06	1.994918	3.989835	1.016572	34.8	39.7	4.9	980.3324	996.578476	0.9965785
V 1,7 Room b (peristyle) Pipe leading to now lost pipe with a tap at the eastern porticoe	3	2.1	2.785	3.950478	7.900956	3.807137	34.8	39.7	4.9	980.3324	3732.259447	3.7322594
V 1,7 Room b (peristyle) Pipe leading to fountains in southern porticoe first part	2	1.3	2	2.568668	5.137337	1.570796	34.8	39.7	4.9	980.3324	1539.902601	1.5399026
V 1,7 Room b (peristyle) Pipe leading to fountains in southern porticoe second part	2.4	2	1.87	3.378868	6.757736	2.903033	34.8	39.7	4.9	980.3324	2845.937642	2.8459376
V 1,7 Room 10 (corridor) Pipe in northern part of corridor	4.9	3.8	4.1	6.704034	13.40807	11.26845	34.8	39.7	4.9	980.3324	11046.82934	11.046829
V 1,7 Room 10 (corridor) Pipe at the door to south	4.2	2.8	4.1	5.436895	10.87379	7.096168	34.8	39.7	4.9	980.3324	6956.603899	6.9566039

V 1, 28 Room b	8.2	4.8	9.1	10.20185	20.40369	23.79359	34.8	39.7	4.9	980.3324	23325.63235	23.325632
IX 3, 5/24 Room 17 (stairs) Pipe in stairs	5	4	4.07	6.915272	13.83054	12.06078	30.76	36.2	5.44	1032.939	12458.05589	12.458056
IX 3, 5/24 Room 18 (garden) Pipe entering room	4	3	3.47	5.397954	10.79591	7.242865	32.2	36.2	4	885.7381	6415.281476	6.4152815
IX 3, 5/24 Room 18 (garden) Westward pipe from distribution box	4	3	3.47	5.397954	10.79591	7.242865	32.2	36.2	4	885.7381	6415.281476	6.4152815
IX 3, 5/24 Room 20 (corridor)	5	3	5.41	6.266875	12.53375	9.073454	32.38	36.2	3.82	865.5796	7853.79662	7.8537966
IX 3, 19 - 20 Room 121 Pipe at the threshold to room 122	4.8	3.65	4.1	6.827178	13.65436	10.59253	31.19	36.2	5.01	991.2751	10500.1122	10.500112
IX 3, 19 - 20 Room 121 Pipe 65 cm after the threshold	4.4	3.4	3.7	6.008377	12.01675	9.040994	31.19	36.2	5.01	991.2751	8962.112467	8.9621125
IX 3, 19 - 20 Room 121 Pipe along the west wall between threshold and the branching	4.6	3.7	4.166	6.110618	12.22124	9.17517	31.19	36.2	5.01	991.2751	9095.117492	9.0951175
IX 3, 19 - 20 Room 121 Pipe from first branching towards center of the room	3.5	3	2.66	4.979309	9.958618	6.329689	31.19	36.2	5.01	991.2751	6274.463261	6.2744633
IX 3, 19 - 20 Room 121 Pipe from first branching towards south wall	5	3.9	4.39	6.717331	13.43466	11.18164	31.19	36.2	5.01	991.2751	11084.07809	11.084078
IX 3, 19 - 20 Room 121	3.6	2.8	3.01	4.926836	9.853673	6.086966	31.19	36.2	5.01	991.2751	6033.858078	6.0338581
IX 3, 19 - 20 Room 121 Pipe from second branching towards north	3.5	3	2.66	4.979309	9.958618	6.329689	31.19	36.2	5.01	991.2751	6274.463261	6.2744633

IX 3, 18 Room 107 near north wall	4.4	3.7	3.399	6.216808	12.43362	9.841624	31.19	36.2	5.01	991.2751	9755.756437	9.7557564

Pipes with one known dimension

Location	Diameter	Perimeter	Area	Asl of pipe	Asl of tower	Head	Velocity	VolFlowRate	Litre/s
V 1, 7 Room I (culina) Westward pipe from southern box	6.3	19.79203	31.17245	34.8	39.7	4.9	980.3324	30559.37	30.55937
V 1, 7 Room I (culina) Eastward pipe from northern box	3.7	11.62389	10.7521	34.8	39.7	4.9	980.3324	10540.63	10.54063
V 1, 7 Room b (peristyle) Pipe from large distribution box with tap towards small basin	3.3	10.36726	8.552986	34.8	39.7	4.9	980.3324	8384.77	8.38477
V 1, 7 Room b (peristyle) Pipe from large distribution box with tap and enlargement towards NE (calculated from measurements of enlargement)	3.8	11.93805	11.34115	34.8	39.7	4.9	980.3324	11118.1	11.1181
V 1, 7 Room b (peristyle) Pipe from large distribution box towards east	2.8	8.796459	6.157522	34.8	39.7	4.9	980.3324	6036.418	6.036418
V 1, 7 Room b (peristyle) Pipe from large distribution box with tap towards east	2.9	9.110619	6.605199	34.8	39.7	4.9	980.3324	6475.29	6.47529
V 1, 7 Room b (peristyle) Pipe from large distribution box with tap towards SE	4.4	13.82301	15.20531	34.8	39.7	4.9	980.3324	14906.26	14.90626
VII 4, 31/51 Room 58 Pipe under the stairs	8	25.13274	50.26548	34.5	39.7	5.2	1009.897	50762.95	50.76295
VII 4, 31/51 Room 18 (peristyle) Pipe in wall of the pool	8	25.13274	50.26548	34.5	39.7	5.2	1009.897	50762.95	50.76295
VII 4, 31/51 Room 18 (*peristyle*) Pipe under threshold to room 31	5	15.70796	19.63495	34.5	39.7	5.2	1009.897	19829.28	19.82928
VII 4, 56 Room 2 (atrium) Pipe inside ceramic pipe	3.5	10.99557	9.621128	34.5	38.7	4.2	907.6115	8732.246	8.732246

VII 4, 56 Room 11	2.5	7.853982	4.908739	34.5	39.7	5.2	1009.897	4957.319	4.957319
VII 4, 56 Room 13 (peristyle) Pipe on top of base	2.5	7.853982	4.908739	34.5	39.7	5.2	1009.897	4957.319	4.957319
VII 4, 56 Room 13 (peristyle) Pipe in eastern wall at the height of 43 cm	1.5	4.712389	1.767146	34.5	39.7	5.2	1009.897	1784.635	1.784635
IX 3, 5/24 Room 18 (garden) Bottom pipe in basin	5	15.70796	19.63495	32.2	36.2	4	885.7381	17391.43	17.39143
IX 3, 5/24 Room 41	5	15.70796	19.63495	32.28	36.2	3.92	876.836	17216.63	17.21663
IX 3, 18 Room 105	5	15.70796	19.63495	30.26	36.2	5.94	1079.366	21193.29	21.19329
IX 3, 18 Room 107 at threshold	4	12.56637	12.56637	30.51	36.2	5.69	1056.407	13275.21	13.27521
IX 3, 19-20 Room 122 Pipe visible at the height of c. 60 cm which is added to asl of room 31.19	1	3.141593	0.785398	31.8	36.2	4.4	928.97	729.6113	0.729611
Castellum aquae middle at 42 m	27.5	86.3938	593.9574	42	43	1	442.8691	263045.3	263.0453
Castellum aquae right pipe at 42 m	22.5	70.68583	397.6078	42	42.6	0.6	343.0449	136397.3	136.3973
Castellum aquae left pipe at 42 m	22.5	70.68583	397.6078	42	42.6	0.6	343.0449	136397.3	136.3973
Castellum aquae middle pipe 10 cm below	27.5	86.3938	593.9574	42.9	43	0.1	140.0475	83182.24	83.18224
Castellum aquae right pipe 10 cm below	22.5	70.68583	397.6078	42.5	42.6	0.1	140.0475	55683.98	55.68398
Castellum aquae left pipe 10 cm below	22.5	70.68583	397.6078	42.5	42.6	0.1	140.0475	55683.98	55.68398